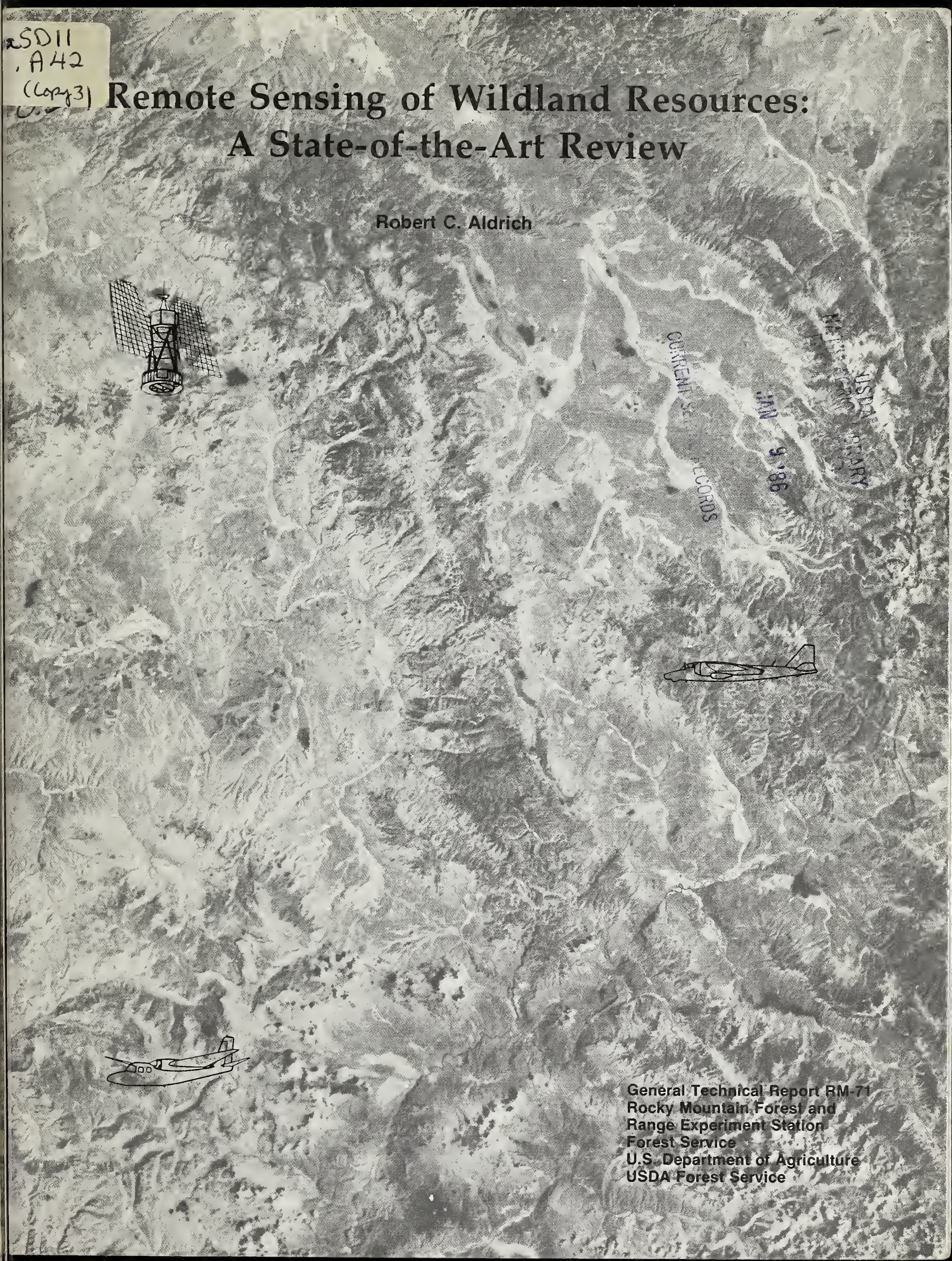
Remote Sensing of Wildland Resources: A State-of-the-Art Review

Robert C. Aldrich



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Abstract

A review, with literature citations, of current remote sensing technology, applications, and costs for wildland resource management, including collection, interpretation, and processing of data gathered through photographic and nonphotographic techniques for classification and mapping, interpretive information for specific applications, measurement of resource parameters, and observations and counts of occurrences.

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INTRODUCTION

Remote sensing is a tool to aid gathering information about land cover with a minimum of ground verification. How much information is extracted from remotely sensed data is dependent upon the type of sensor and the portion of the electromagnetic spectrum (EMS) used, the quality of the data recorded, and certain physical limitations including platform altitude, topography, variations in solar angle and solar altitude, and atmospheric interference. There are other limiting factors involved in processing the data once they have been collected (i.e., regardless of how well data are gathered, improperly processed and/or interpreted data will yield poor information, preventing realization of the full capabilities of remote sensing).

The "state" of something is the sum of the qualities involved in its existence at a particular time and place. The qualities of remote sensing as defined here include the data as well as the data collection, interpretation, and/or data processing. The end result must be cost-effective information useful to resource managers for land use planning and solving wildland management problems. Remote sensing as reviewed in this paper covers both photographic and nonphotographic data including microwave, radar, thermal infrared (thermal IR), ultraviolet (UV), as well as multispectral scanner (MSS) data. Nonimaging radiometers and spectrometers, however, are not included. Remotely sensed data may be interpreted manually (photo interpretation), by automatic data processing (ADP), or by a combination of the two.

TERMINOLOGY

It would be difficult to discuss the state of remote sensing without reference to several basic technical terms. These terms are defined here to avoid confusion and the need for repetition later in the review. A more complete glossary of remote sensing is found in appendix A.

Ground resolution.—For this review, ground resolution refers to the smallest detectable or measureable detail on a remotely sensed image. In aerial photography, ground resolution is a function of scale (camera lens focal length and flying height above ground) and the resolving power of a system. To measure an object or condition on photographic films requires a finer ground resolution than to detect it. This is because of granularity in the processed image and because of light scattering during exposure. Thus, resolution is the ability of an entire remote sensing system, including lens, antennae display, exposure, processing, and other factors, to render a sharply defined image.

The required ground resolution for each application in this review was taken from a U.S. Department of Agriculture (USDA) Forest Service Data Users Requirements Task Force Catalog (see INFORMATION NEEDS—THE USER REQUIREMENTS). Ground resolutions obtainable by each film were based upon system resolving power (including camera lens, film, and image motion during exposure) and were interpreted from Welch (1972) (table 1). The use of trade and company names is for the benefit of the reader; such use does not constitute an official endorsement or approval of any service or product by the USDA to the exclusion of others that may be suitable.

Resolving power.—Resolving power refers to changes in resolution in an image that depend on film, relative lens aperture, lens aberations, and the angular distance of the object from the optical axis. It is usually expressed in number of line pairs (black and white bar targets) visible per millimeter of film. As the field angle (field of view or aperture) of a lens increases, the resolving power decreases. Sometimes a lens is the limiting factor in resolving power of a system if its resolving power is less than the resolving power of other system components. The same logic can be applied to other components of the system; the resolving power of a system can be no better than its weakest component.

[2]*The author wishes to thank Professor Robert C. Heller, University of Idaho; Professor Roger M. Hoffer, Purdue University; Wayne G. Rohde, Technicolor Graphic Services, Inc. (EROS Data Center); and Ray P. Allison, Remote Sensing Coordinator, USDA Forest Service, for their helpful reviews of this paper. Their comments and suggestions lead to many improvements in the manner of presentation as well as content.*

Table 1.—Photographic film and scale requirements to detect and measure USDA Forest Service ground target resolutions[1]

Ground resolution requirement	Photographic requirement by			
	Detection		Measurement	
	IR and CIR[2]	BW and color[2]	IR and CIR[2]	BW and color[2]
m	Photographic scale			
	Aircraft platforms[3]			
0.1	1:3,200	1:5,000	1:1,600	1:2,500
0.3	1:12,500	1:20,000	1:6,400	1:9,600
0.5	1:20,000	1:32,000	1:9,600	1:16,000
1.0	1:40,000	1:64,000	1:20,000	1:32,000
1.5	1:64,000	—[5]	1:32,000	1:46,000
2.0	—[5]	—	1:40,000	1:64,000
3.0	—	—	1:64,000	—[5]
	High altitude and space platforms[4]			
1.0	1:64,000	1:125,000	1:32,000	1:64,000
1.5	1:92,000	1:184,000	1:46,000	1:92,000
2.0	1:125,000	1:250,000	1:64,000	1:125,000
3.0	1:184,000	1:320,000	1:92,000	1:160,000
4.0	1:250,000	1:500,000	1:125,000	1:250,000
5.0	1:310,000	1:620,000	1:155,000	1:310,000
10.0	1:500,000	1:1,000,000	1:250,000	1:500,000
30.0	1:1,500,000	1:3,000,000	1:750,000	1:1,500,000
80.0	1:3,900,000	1:6,000,000	1:2,100,000	1:2,600,000

[1]*Tabular values were read from graphs adapted from figure 9 of Welch (1972) and rounded for consistency.*

[2]*BW—panchromatic, IR—infrared, color—normal color, CIR—color infrared (Aerochrome Infrared)*

[3]*150- to 9,200-m altitude; films referred to are Eastman Kodak Infrared Aerographic 2424 (IR), Aerochrome Infrared 2443 (CIR), Panatomic 3410 (BW), Aerocolor 2445 (color), and Aerochrome MS 2448 color.*

[4]*9,200-19,800 m and above 190 km altitude; films referred to are Eastman Kodak High Definition Aerochrome Infrared SO-127 (CIR), High Definition Aerial 3414 (BW), and Aerial Color, SO-242 (color).*

[5]*Theoretically, scales smaller than 1:64,000 cannot be obtained from a 9,200-m altitude unless a lens focal length shorter than 6 inches (150 mm) is used. There is no precedence for doing this. Since lower resolution requirements can be achieved at 1:64,000, the chart is not extended beyond this point.*

Contrast.—Contrast is the distinction between two objects on remotely sensed images and is dependent upon the ratio of the energy reflected by those two objects, the sensor sensitivity, solar illuminance, atmospheric luminance, and atmospheric transmittance (American Society of Photogrammetry 1975). The resolving power of aerial films is usually given in terms of contrast ratios of 1,000:1 or 1.6:1, high contrast targets and low contrast targets, respectively. In reality most natural objects have ratios of less than 5:1 and contrast ratios closer to 2:1 when other factors cited are taken into account.

Scale.—Scale refers to a representative fraction, or the ratio of a unit of measured distance on the image (usually 1 inch) to the measured distance represented on the ground expressed in the same units of measure. The smaller the fraction (i.e., the larger the divisor of the fraction) the smaller the scale. Small scales in this review lie between 1:30,000 and 1:200,000, medium scales lie between 1:12,000 and 1:30,000, and large scales are from 1:500 to 1:12,000. Imagery smaller than 1:200,000 (including satellite imagery) is considered very small-scale imagery and requires special viewing equipment with enlarging stereo or monoscopic optical systems (table 2).

The finest detail recorded on photographic film today can only be observed by magnification. In effect, magnification corresponds to a change in scale (Welch 1972). For obvious reasons, then, any reference to a terrain feature observed on a photograph of a certain scale means very little from a systems evaluation point of view. The image-forming properties of the film, the camera system, and the additional magnification must also be referred to (table 2).

Electromagnetic spectrum.—The EMS is an ordered array of known electromagnetic radiations (energy) (American Society of Photogrammetry 1975). In this review only those portions of the EMS known to be useful for gathering wildland informa-

tion are considered (fig. 1). These portions include UV (0.28-0.4 μm), visible (0.4-0.7 μm), photo IR (0.7-0.9 μm), near IR (0.9-1.3 μm and 1.3-3.0 μm), middle IR (3.0-13.8 μm), and the microwave wavelengths of radio energy (0.1-77.0 cm). The microwave portion of the EMS is further divided into passive (0.1-3.0 cm) and active microwave (radar, 0.5-77.0 cm).

Band.—In this paper "band" refers to a selection of wavelengths in the EMS (e.g., from 0.6 to 0.7 μm is defined as the red band of the visible spectrum) or it can be a range of radar frequencies referred to as the X-, K- or L-band.

Instantaneous field of view.—Instantaneous field of view (IFOV) denotes the narrow field of view designed into scanning radiometer systems (thermal scanners and MSS's), so that, while about 120° may be under scan at any one instant, only electromagnetic energy from the small area covered by the field of view is being recorded (American

Table 2.—Magnification and instrumentation necessary to interpret and/or classify and map from photographic remote sensing imagery

Photographic scale		Required magnification[2]	Data type[3]	Recommended instrument or method[4]
Representative fraction	Code			
		—Number of enlargements—		
		Stereoscopic		
1:1,600	01	1.5	P	PS
1:2,500	02	1.5	P	PS
1:3,200	03	1.5	P	PS
1:5,000	04	1.5	P	PS,MS,SS
1:6,400	05	1.5	P	PS,MS,SS
1:9,600	06	1.5	P	PS,MS,SS
1:12,000	07	1.5	P	PS,MS,SS
1:16,000	08	1.5	P	PS,MS,SS
1:20,000	09	1.5	P	PS,MS,SS
1:32,000	10	2.0	P	MS,SS
1:40,000	11	3.0	P	MS,SS,ZS
1:46,000	12	3.0	P	MS,SS,ZS
1:64,000	13	3.5	P	MS,SS,ZTS,ZS
1:83,000	14	4.0	P	ZTS,MS,SS,ZS
1:92,000	15	4.5	P	ZTS,MS,SS,ZS
1:100,000	16	5.0	P	ZTS,SS,ZS
1:125,000	17	6.0	P	ZTS,SS,ZS
1:150,000	18	6.5	P	ZTS,SS,ZS
1:155,000	19	6.5	P	ZTS,SS,ZS
1:160,000	20	7.0	P	ZTS,SS,ZS
1:184,000	21	8.5	P	SS,ZS
1:200,000	22	9.0	P	SS,ZS
		Monoscopic		
1:250,000	23	11.0	P,D	SM,PE(ZTS),DIAS
1:310,000	24	13.0	P,D	SM,PE(ZTS),DIAS
1:320,000	25	14.0	P,D	SM,PE(ZTS),DIAS
1:375,000	26	15.0	P,D	SM,PE(ZTS),DIAS
1:500,000	27	20.0	P,D	SM,PE(ZTS),DIAS
1:620,000	28	23.0	P,D	SM,PE(ZTS),DIAS
1:750,000	29	26.0	P,D	SM,PE(ZTS),DIAS
1:1,000,000	30	35.0	P,D	SM,PE(ZTS),DIAS
1:1,250,000	31	39.0	D,P	DIAS,PE(ZTS)
1:1,500,000	32	45.0	D,P	DIAS,PE(ZTS)
1:2,100,000	33	50.0	D,P	DIAS,PE(ZTS)
1:2,600,000	34	55.0	D,P	DIAS,PE(ZTS)
1:3,000,000	35	60.0	D,P	DIAS,PE(ZTS)
1:3,900,000	36	70.0	D,P	DIAS,PE(ZTS)

[1]*Usually 70-mm format*
[2]*Taken from figure 17 of Welch (1972).*
[3]*P—photographs*
D—digitized photographic transparencies.
[4]*PS—pocket stereoscope.*
MS—mirror stereoscope (2X).
SS—scanning stereoscope (2X, 4X, 9X).
ZS—zoom stereoscope (2.5-60X).
SM—stereo microscope (2.5-60X).
ZTS—zoom transfer scope (1-13X).
DIAS—digital image analysis system.
PE—photo enlargement.

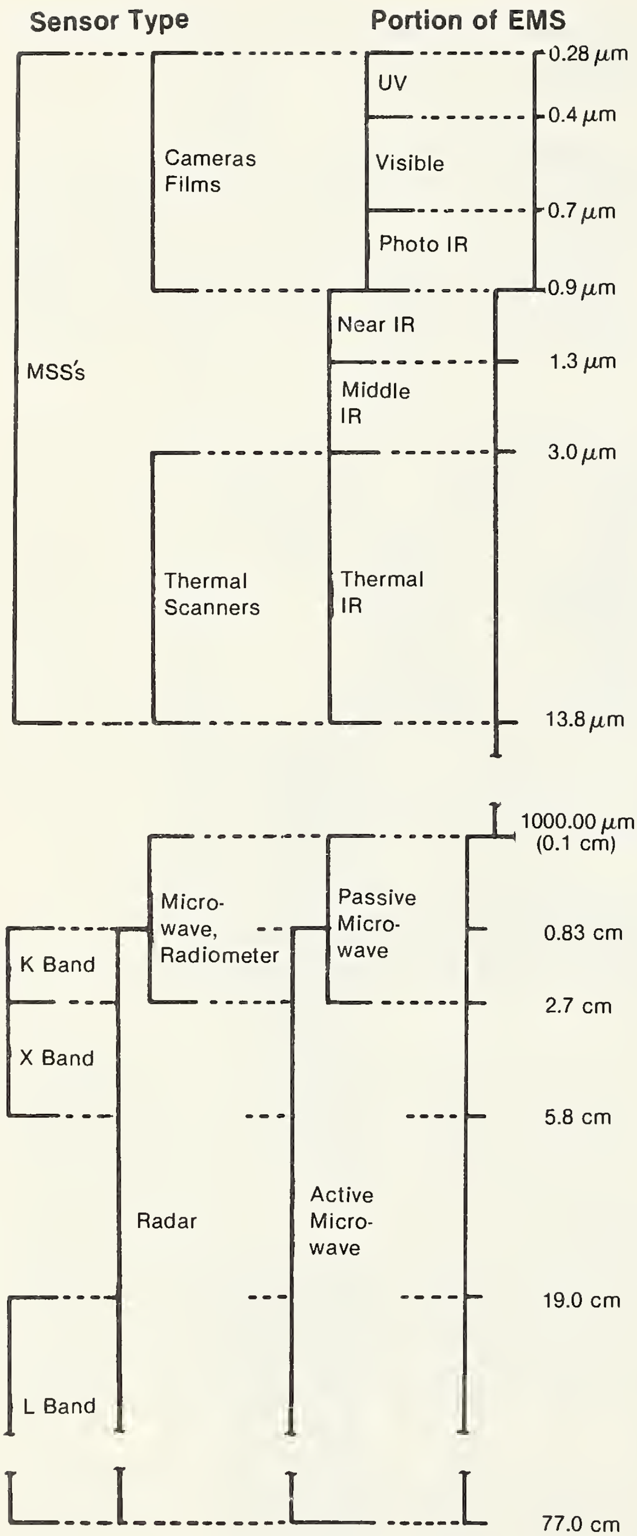

Figure 1.—Useful portions of the electromagnetic spectrum (EMS) and the most effective sensor type. Portions of the EMS are not drawn to scale.

Society of Photogrammetry 1975). For example, the four-band MSS's on Landsat-2 and Landsat-3 subtend an IFOV of 79 m on a side from 920 km above the earth. A cross track IFOV of 57 m is obtained by resampling the signals across the swath at the scanner's electronics output.

Imaging sensors.—In the broadest sense used here, imaging sensors include cameras and films and optical-mechanical scanners—including both thermal scanners and MSS's. These sensors, as well as photographic sensors, are optical devices and are passive sensing systems. Although radar and passive microwave systems are considered imaging systems, they are not optical devices.

BACKGROUND

A review of the state of remote sensing is a formidable task when one considers the abundance of literature printed on the subject during the past 10 years. This abundance has been caused largely by the Earth Resources Survey Program of the National Aeronautics and Space Administration (NASA). Through this program NASA has made outstanding contributions to the development of remote sensing technology. It is unfortunate, however, that not all of what is written is worthy. Much of the "oversell" of remote sensing in recent years has come from overly enthusiastic individuals and their agencies. Many times speculative statements at the end of inconclusive studies have been quoted out of context (Buys 1973) and blown out of proportion, resulting in a credibility gap between the remote sensing community and the user community (Murtha 1976).

Space and time do not permit a thorough review of every paper published on wildland resources during the past 10 years. However, a careful review of indexes to scientific journals, publications of abstracts, and technical information digests revealed pertinent sources of information which were reviewed in greater detail. Source materials included *Photogrammetric Engineering and Remote Sensing, Remote Sensing of Environment, Forest Science, Journal of Forestry, Journal of Range Management, Applied Ecology Abstracts, Forestry Abstracts, Selected Water Resource Abstracts, Wildlife Review, Forestry Chronicle, National Technical Information Service Index, LANDSAT Newsletter, NASA/SCAN Notification, Manual of Remote Sensing,* proceedings of symposia, and research papers and reports. Not every wildland resource subject is addressed in the literature; however, information reported can be interpreted for subjects that are neglected. Publications on many subjects were inconclusive, and many times conclusions overstated the results of experiments.

INFORMATION NEEDS— THE USER REQUIREMENTS

To manage wildlands, information is needed to address all USDA Forest Service resource systems (forest and rangeland, outdoor recreation and wilderness, wildlife and fish, range, timber, and water). To make an assessment of the potential effects of alternative land uses on resource systems requires basic information on soils, vegetative cover, water, landform (topography), and climate and their relationship to each other. An inventory of current and potential productivity of land is also needed by resource managers making land use and management decisions. Some local management and planning decisions require mapped or pinpointed information. Other decisions at the state, regional, and national levels may be based upon statistical data derived from extensive samples. Regardless, the basic information required to satisfy program plans (national, state, or regional), environmental impact statements, management plans, and day-to-day management operations differs only in resolution. For example, national planners may need to know timber volume by broad softwood or hardwood categories by regions, regional planners may need timber volume by states by broad forest types, and state planners may need timber volume by counties by specific forest types. The parameter to be measured, accuracy required, and the way the data are formatted will differ accordingly.

In 1978 a USDA Remote Sensing User Requirements Task Force (required by the Secretary's Memorandum No. 1822 dated August 17, 1973) identified over 800 USDA Forest Service information requirements. These requirements were compiled in a computer printout called the Data Users Requirements Task Force Catalog. Each requirement was addressed in terms of its current potential or its future potential for being classified, interpreted, or measured by remote sensing.

The USDA Forest Service's information requirements attainable now or by further remote sensing research and development were examined and recommendations were made for either aerial or satellite platforms, the required ground resolution, and the best remote sensor type. Platforms (vehicle type and altitude) in this present review are considered a consequence of the sensor type and the ground resolution required and not an independent, and thus limiting factor for sensor selection.

A review of the remote sensing user requirements revealed that most requirements can be divided into four major groups based upon application.

Classification and mapping application.—These applications require some observational and interpretive skills to delineate homogeneous areas of cover. Delineations might be made by drawing a boundary line or by point sampling with listings of points by cover type. Units of land are classified by vegetative cover, nonvegetative cover, land use, land form, or disturbance.

Interpretive information for specific applications.—These applications may require some observational and measurement skills to answer a management problem within a designated area or at a certain location. Information interpreted from remotely sensed data in this sense does not result in a map. It could confirm that a certain condition exists, locate and flag the condition, and provide certain corollary information needed to manage condition. Some examples might be the location of an unusual stress condition, potential landslide, geological hazards, soil erosion, oil slicks, and other water pollutants.

Measurements of resource parameters.—These measurements include linear distances, heights, numbers, area, and other expressions of the size, quantity, or quality of basic resources.

Observation and counts of occurrences.—This category is defined as the determination of the presence or absence of something—a building, structure, cars, people, animals, road washouts, erosion, and others.

Two hundred eleven nonoverlapping user requirements (app. B) were extracted from the User Requirements Catalog and assigned to 1 of these 4 major and 45 secondary application areas (table 3). The assignment of a particular requirement to one application area rather than another was based on the author's experienced judgment. The requirements were organized in this way to reduce the number of application problems to a reasonable number for this review.

REMOTE SENSING SYSTEMS

Before discussing the state of remote sensing for wildland resources, it would be appropriate to review current photographic and nonphotographic data acquisition systems.

PHOTOGRAPHIC SENSING SYSTEMS

Cameras and films were used to collect wildland resource information long before remote sensing

Table 3.—Distribution of remote sensing application problems by category[1]

	Application	Number of items
I.	Classification and mapping	87
A.	Vegetative cover	24
B.	Nonvegetative cover	18
C.	Land use	1
D.	Land forms	17
E.	Disturbance	27
II.	Interpretive	36
A.	Land use	3
B.	Wildlife habitat	6
C.	Land use (vegetation)	1
D.	Fire utilization corridor	1
E.	Fuel type	1
F.	Grazeable woodland	1
G.	Vegetative condition	5
H.	Unstable conditions	1
I.	Rock slide barriers	1
J.	Avalanche path	1
K.	Geology	4
L.	Soil type	2
M.	Minerals and construction materials	2
N.	Phenology	3
O.	Tree point occupied	1
P.	Sensecent or dystrophic lakes	1
Q.	Hydrologic condition	1
R.	Natural open areas	1
III.	Measurements	60
A.	Tree and stand	22
B.	Grasses	2
C.	Forbs	1
D.	Brush and shrubs	4
E.	Water	7
F.	Snow	1
G.	Rock slides	2
H.	Gully erosion	3
I.	Sheet erosion	1
J.	Biomass	9
K.	Land use	2
L.	Disturbed area	1
M.	Area of mortality	1
N.	Animal counts	1
O.	Fuel	1
P.	Fire area burned	1
Q.	Dimension of structures	1
IV.	Observations and counts	28
A.	Building and structure	4
B.	Water structures	1
C.	Transportation	3
D.	Recreation	9
E.	Wildlife	2
	Total	211

[1]*Summarized from the U.S. Department of Agriculture, Remote Sensing User Requirements Task Force, Catalog of Requirements, 1978.*

became the popular term for gathering information about objects without physical contact. Some people, however, never speak of photography in the same breath with remote sensing. One explanation for this might be that remote sensing as a technology seemed to evolve with the development of optical-mechanical scanners, other sophisticated sensors, and computer analysis of digital data. This evolutionary association remains to this day. Many of the most renowned centers of remote sensing do little if any research and development in photographic data acquisition and interpretation, although aerial photo data supply most of the ground truth for verification of other remote sensing study results.

Photographic sensors include both camera optics and films. Although cameras are not specified by name or by manufacturer in this review, all references to cameras include the best available mapping cameras and reconnaissance cameras, as well as advanced camera systems for high-altitude and satellite applications. Mapping camera optics are generally capable of resolving 30-40 line pairs per mm (at 1.6:1 contrast). Some high-altitude reconnaissance cameras can resolve over 100 line pairs per mm (American Society of Photogrammetry 1975). It is usually the film, not the camera optics, that restrict ground resolutions obtained by photographic systems.

Films available for aerial photography include panchromatic (BW), IR, color, and color infrared (CIR). The spectral sensitivity of BW and color films are very similar as are sensitivities of IR and CIR films. BW and color films are generally sensitive to the visible portion of the EMS from 0.4 μm (blue) to 0.7 μm (red). IR and CIR films are both sensitive to the visible portion of the EMS but the sensitivity is extended to about 0.9 μm to include some reflected IR. In use, IR and CIR films are usually filtered with a minus-blue (W-12) filter to cut out the blue and blue-green wavelengths and improve haze penetration. Other filters that cut out the blue and blue-green portions of the EMS have been used successfully to accentuate the orange-red portion of the EMS on CIR film. On IR film used with either a Wratten 25A (red) or 89B (dark red) filter, broadleaved vegetation appears lighter in tone, whereas water and moist soil appear darker in tone. The theory of imaging with photographic sensors has been well documented by Heller (1970).

Film speeds, resolving power, and granularity are reported in Eastman Kodak Publication M-57 (1977). Generally, as film speed increases resolving power decreases. All references to film resolving power or resolution in this review paper are for low contrast subjects (1.6:1) typical of wildland resources.

NONPHOTOGRAPHIC SENSING SYSTEMS

Nonphotographic sensors operate in portions of the EMS from UV through the microwave regions. They include optical-mechanical scanners for multispectral sensing, thermal IR, and active and passive microwave systems.

Multispectral Scanner Systems

MSS's observe the scene under the aircraft or satellite platform in a number of discrete bands of the EMS. Multiple detectors capture and measure reflected energy that can include ultraviolet (0.28-0.4 μm), visible (0.4-0.7 μm), near (0.7-1.3 μm), medium (1.3-3.0 μm), and thermal (3.0-13.8 μm) IR portions of the EMS. This is usually accomplished by allowing the entrance slit of a spectrometer to act as the scanner aperture. Each detector in an array observes the same resolution element of the scene below but in a different wavelength region. Output signals from the detector array can be combined to determine the spectral distribution of the radiation from each resolution element of a scene. Collecting data in this manner provides multispectral data that are registered, easily recorded onto photographic film, and directly compatible with computer processing systems. Commercial systems are available that record data in narrow wavelength bands over the range from UV to far IR.

The dominant factor in determining spectral and spatial resolution of MSS systems is the entrance slit of the spectrometer. The resolution IFOV's for commercially available airborne scanners range from 1 to 3 mrad, or in terms of ground resolution, 1 and 3 m, respectively, for each 1,000 m of altitude above ground. The operational MSS's on Landsat-2 and Landsat-3 have resolution IFOV's of 0.086 mrad (American Society of Photogrammetry 1975), that is, at 920 km above the earth, the ground resolution would be approximately 80 m.

Calibration is an area of primary importance in using MSS's. These calibrations are described in detail in American Society of Photogrammetry (1975), and elsewhere. It is sufficient here to acknowledge that such calibration procedures are important and do exist to measure the ability of an instrument to consistently reproduce the spectral and spatial distribution of radiation from various size elements in the scene. Other necessary corrections include those for lateral distortion (beam velocity while scanning the Earth is nonlinear), motion of the aircraft, and electronically generated image distortions. Acquiring dependable data from optical-mechanical scanners is a complex task.

Thermal Scanner Systems

A thermal scanner consists of a rotating prism mirror and a telescope to focus radiation from a small portion of the Earth's surface. The rotating prism mirror causes the field of view to move smoothly across the object plane (Holter 1970). Each face on the mirror is inclined 45° to the axis of rotation, and as the prism mirror rotates it reflects IR photons through the telescope to a detector. The heart of the scanner is the detector, which transduces (transforms) the incident IR radiation into an electric signal. These signals are most commonly used to record images on a cathode ray tube (CRT) in synchronism with the IR scanner. The face of the tube can be photographed as a permanent record. Signals are also recorded on magnetic tape to display later on a CRT and pictorial record.

Commercially available scanners have IFOV resolutions of 1.5-3.0 mrad (American Society of Photogrammetry 1975) and focal lengths of 2.5-30.0 cm. The IFOV resolutions translate to ground resolutions of 1.5 and 3.0 m, respectively, for every 1,000 m of platform altitude above ground. For example, the thermal band on Landsat-3 has a resolution IFOV of 0.26 mrad which translates to a ground resolution of 240 m at 920 km above ground.[3] The Heat Capacity Mapping Mission (HCMM) satellite launched in May 1978 has a single-channel thermal sensor on board recording over a 1,120-km swath width with a 500-m ground resolution.

Daytime operations for thermal scanners are confined to atmospheric windows of 4.5-5.5 μm and 8.5-13.5 μm with exception of forest fires and volcanic activity (American Society of Photogrammetry 1975). Thermal scanners operate equally well at night and in the period when most forest fire data are collected. Thermal scanners vary by method of data recording and optional ancillary equipment in addition to their performance parameters—resolution, sensitivity, and velocity/height ratio (v/h).

Microwave Sensor Systems

Microwave sensors, including both active and passive systems, are thoroughly described for the nontechnician in American Society of Photogrammetry (1975) and Holter (1970). Active microwave systems (radar) are those that provide their own illumination of the target. In other words, a known signal is transmitted to reflect off the target and back to a receiver. The portion of the signal that is reflected back to the receiver is a function of the

[3]The thermal band sensor on Landsat-3 failed on July 11, 1978, and was turned off. Diagnostic tests are being performed to determine the cause of failure. Landsat Newsletter 20, April 1, 1978.

transmitted power, the antennae size, the wavelength of the transmitted energy, the scattering properties of the ground target, the angle of incidence, the signal width, and the distance to the target. The back scattered energy is converted into a spot of light which is regulated according to the strength of the received signal to produce a BW line scan image. A strong return signal is indicated by bright tones whereas a weak return signal is indicated by dark tones.

Passive microwave sensors are not as well developed as sensors in other portions of the EMS. A microwave radiometer is a passive system, meaning signals received by the radiometer are emitted by the target itself. Unfortunately, the self-emitted radio signal is much less than you would find in the IR portion of the EMS. As a result, receivers must be extremely sensitive and have little internal noise. An imaging microwave radiometer is much like the receiver of a radar system. The utility of passive sensors for wildland resources has not been fully explored and very little is known upon which to draw conclusions.

Ground resolution of both active and passive microwave systems is normally poorer than the resolution of sensors in the visible and IR regions. This is because resolution is directly proportional to wavelength, and the shortest microwavelength used is a factor of 100 larger than the wavelength for thermal IR scanning. A fine-angular-resolution for active microwave sensors requires a very large aperture. Generally speaking, resolution capabilities of commercially available imaging radar systems average about 15 m (3-30 m). Most of these systems are confined to the X-band (2.7-5.8 cm). SeaSat, which was launched in June 1978 and became inoperable in November 1978, operated in the L-band (19.0-77.0 cm) and observed ocean dynamics by night and day with a ground resolution of 25 m from an altitude of 800 km.

Some general characteristics of active microwave systems are (1) their ground resolution is generally poorer than that of optical systems; (2) they can sense through cloud cover and some rain; (3) their responses are functions of frequency (or wavelength), polarization, and look angle (as are responses in other portions of the EMS); (4) signal polarization is often used as a discriminant; (5) observational angles well away from vertical are best because of the geometry of radar range measurements; and (6) they can collect data day or night (American Society of Photogrammetry 1975).

Return-Beam Vidicon Systems

The three-sensor return-beam vidicon (RBV) cameras on board Landsat-1 and Landsat-2 are probably the most familiar RBV systems in use today. However, only a limited number of frames of RBV data were ever recorded on Landsat-1 and Landsat-2. Landsat-1 ceased to function on January 6, 1978. These systems represented the state of the art until Landsat-3 was launched on March 5, 1978. RBV cameras are essentially high resolution (5,000 lines per picture) television cameras.

Cameras on board Landsat-1 and Landsat-2 operate in three spectral bands (0.475-0.575 μm, 0.580-0.680 μm, and 0.690-0.830 μm), cover an area on the ground of 185 by 185 km, and have a nominal ground resolution of approximately 44 m for high-contrast objects and 95 m for low-contrast subjects (National Aeronautics and Space Administration 1976a). Landsat-3 cameras are different (National Aeronautics and Space Administration 1976b). They are two identical RBV cameras operating in the broad spectral band from 0.5 to 0.75 μm. These BW-sensitive cameras have a ground resolution of approximately 22 and 42 m for high contrast and low contrast subjects, respectively. This was made possible by doubling the camera focal lengths. The camera IFOV's are aligned side-by-side to view side-by-side nominal 99-km^2 ground scenes with 15-km side laps yielding a 183- by 99-km scene. Two successive pairs of RBV images will nominally cover the same area as one MSS frame. Video signals from the cameras are recorded on magnetic tape at ground stations, where processed tapes and hard copy reproductions are produced with annotations for time and location of the imagery. Although Landsat RBV data, available since 1972, have not been fully evaluated for wildland resource information, the increased spatial resolution of Landsat-3 RBV data shows great promise for mapping and updating maps.

THE STATE OF REMOTE SENSING APPLICATIONS—PHOTOGRAPHIC DATA

Photographic data have been used in wildland resource management activities for over 40 years. Timber inventories, range inventories, and wildlife habitat mapping were purposes for which conventional medium-scaled BW aerial photographs were regularly used (Dolke 1937; Garver 1948; Harris 1951; and Aldrich 1953, 1968). Interpretation used to be based upon photographic tone, texture, shape, size, patterns, shadows, topographic position, and associations. Conventional photointerpretation today is based upon these same variables but with many more options. In 1978 the photointerpreter's job was easier, more satisfying, and done with greater confidence because many color combinations of hue, chroma, and value as

well as IR sensitivity are available. Healthy human eyes can discriminate 1,000 times as many tints and shades of color as they can tints and shades of gray (Ray and Fischer 1957). In addition, improvements in the spectral quality, resolving power and speed of camera lenses and films (BW, IR, color, and CIR), and the use of band pass filters have made it possible to fly aerial photography from both low altitudes (150-3,659 m) and high altitudes (9,200-19,800 m). The information content is equal to or better than the medium-scale BW photography (3,659-9,200 m) of years gone by. Photographs from space, although available only for limited geographic areas following NASA's Gemini, Apollo, and Skylab space programs (1964-1974), have shown that medium resolution imagery can be beneficial in boundary delineations (Colwell 1968, Draeger 1968). In addition, space photographs have other advantages that may prove to be useful for digitizing photographic images to use in interactive ADP systems.

CLASSIFICATION AND MAPPING

Vegetative cover classification is the most important user requirement and the most often used parameter in recent studies of remotely sensed data. But disturbance and nonvegetated cover classification and mapping are also important user requirements. The level in a land cover classification hierarchy, and/or the degree of mapping detail and accuracy needed, dictates the best film and scale for a particular job. Eighty percent or more of the references to applications of remote sensing in wildland managment activities are included in this category.

Conventional Interpretation

Medium-scale aerial photography will continue to be the primary source of USDA Forest Service remotely sensed information. Large-scale aerial photographs will become more economically feasible in the future as the cost of field work increases. The future of small-scale aerial photographs and space imagery rests on cost benefits, availability, and development of computer image analysis techniques.

General Interpretation Information

The key to successful conventional interpretations of vegetative cover on any photographic scale is the timing of the photographic data to take full advantage of phenological developments. For example, in the northern temperate zone, vegetation is best interpreted on CIR film in early spring before new deciduous foliage covers the ground and in the fall when deciduous foliage increases in IR reflectance (Hunter and Bird 1970). On high-altitude CIR film, the best time of year for forest type differentiation in the southeastern United States is from late fall, after the leaf fall, to early spring (Aldrich and Greentree 1972). Here, leafless conditions are important to differentiate between the upland and bottomland deciduous types. Moisture in the soil and in the humus layer absorbs IR radiation causing a dark blue response on CIR film taken over deciduous forests. Also, according to Hunter and Bird (1970), the drier the site the greater the leaf reflectance will be in the visible spectrum.

Another important but often misunderstood point is the effect of vegetation age on visible and IR reflectance. For instance, old leaves of deciduous trees reflect more energy than young tree foliage (Hunter and Bird 1970). Furthermore, reflectance from hardwood (deciduous) foliage decreases during early weeks of the growing season, remains fairly constant until after the middle of summer, then rises rapidly during the autumn color change. This explains why midsummer photographs show little discrimination between species. Variations in reflectance from deciduous foliage are minimized during autumn, and conifer foliage reflects significantly less energy toward the end of the growing season. This difference helps to accentuate the deciduous/conifer boundary line for type mapping.

Large- and Medium-Scale Photography

Vegetative cover classification.—Vegetative cover classification to the level of species composition could become more important as the cost of field data rises. Large scales would be needed to accurately identify and map individual tree and lesser vegetation in complex deciduous and coniferous associations found in the central, eastern, and southern United States. This use requires scales larger than 1:4,000. Normal color and CIR films are necessary to separate the individual species. Generally, normal color has proven to be best for tree species (Heller et al. 1966, Aldred 1976, Miller et al. 1976, Sayn-Wittgenstein et al. 1978) and, at the peak of flowering, CIR is best for grasses and forbs (Driscoll 1969, Driscoll and Coleman 1974). According to Tueller et al. (1972), all tree species, most shrubs, and some grasses and forbs can be accurately identified on 70-mm large-scale aerial photography.

There have been a number of developments for application of medium-scale BW, color, and CIR photography for vegetation classification and mapping during the past 15 years, including the use of 1:15,840 color photography by the USDA Forest Service. Aldrich and Norick (1969), using nonstereo

1:20,000 scale BW photographs, showed that post sampling stratification by forest type and volume could improve sampling efficiency on national forest surveys. Johnson and Sellman (1974, 1975, 1977) developed dichotomous interpretation keys in Alabama to aid stratifying forest cover into meaningful cover types on 1:20,000 BW photographs. They used slope and aspect as well as stand density, tree heights, crown widths, and tone as variables in their keys. For wetland mapping, CIR at 1:24,000 scale was found to be most suitable for delineating types down to a 2.5-acre (1.0-ha) minimum (Werth et al. 1977). In contrast, Scher and Tueller (1973) found that 1:10,000 color and CIR photographs exposed in late summer early in the morning were best for mapping wetlands in Nevada. For operational wetland mapping in New Jersey and New York, Brown (1978) found that a combination of 1:12,000 CIR and color films was best. Austin and Adams (1978) had a similar experience mapping marine plant resources. They found that color was most useful for definition of submerged vegetation to depths of 7 m. However, CIR and color together provided the best definition of above-water intertidal seaweed vegetation. A scale of 1:10,000 was used to map 11 vegetation communities.

Disturbances.—Detecting and mapping disturbances to the vegetative cover requires careful consideration of reflectance patterns more than any other user requirement. Water deficiency stress caused by insects, disease, or other agents must be detected and mapped on photographs that are timed to take advantage of foliage color changes. This means that CIR and color film must be used to capture the subtleties of color differences between healthy and stressed trees. The photographic scale depends on the ground resolution required (size of the trees or affected part). For example, white pine weevils (*Pissodes strobi* (Peck)) often only affect the terminal growth of seedlings and saplings and are accurately detected and counted only on 1:600 scale sample photography (Aldrich et al. 1959). Individual trees attacked and killed by bark beetles are detected on 1:7,920 or larger scale color or CIR film (Heller 1974). Heller also claims that if small infestations of one or two trees can be overlooked, a scale of 1:32,000 using CIR film is the most efficient. In 1976 a high resolution panoramic camera (Optical Bar; KA80A) was evaluated in a dead timber pilot study (Weber 1977). This camera takes photographs 4.5 inches wide by 50.26 inches long (11.4 by 127.7 cm). The results were encouraging enough to photograph 20 national forests in the western United States in 1978 at 1:33,000 scale with CIR film to assess the impact of forest insects. Regardless of scale, neither color nor CIR photography is useful as a previsual detector of bark-beetle-infested conifer trees. Although Colwell (1956) reported that stress caused by a disease in wheat could be detected previsually on CIR film, there has been no corroboration of this finding for either conifer or deciduous forest trees.

Aerial photographs have not been widely used as a tool to survey defoliators of either conifer or deciduous forests. This is primarily because defoliators are not as important or as serious a problem as bark beetles. Defoliators do not usually kill trees except over several years of repeated defoliation and the benefits usually will not justify the expense of photography. Visual survey techniques from an aircraft (Heller 1974) are more suitable to monitor these and other less important insect and disease problems. Special purpose sampling photography, however, can be beneficial for assessing defoliator damage both before and after control efforts (Wear and Curtis 1974). Furthermore, Ashley et al. (1978) found that 1:15,840 CIR photography in late summer could define forest with various stages of feeding stress, recovery, and mortality caused by spruce budworm (*Choristoneura fumiferana* (Clemens)) in Maine. The technique is considered feasible for locating stands of balsam fir and spruce needing salvage or presalvage cutting. In this example photography is justified by the followup management activity. Sometimes, however, sampling photography is easier to justify. For example, large-scale color photographs (1:1,584) could be a useful sampling technique in monitoring spruce budworm defoliation and its effects over time. Photographs taken annually for 10 years over several spruce-fir plots with varying degrees of spruce budworm defoliation in Minnesota not only showed the different levels of damage but were also helpful in measuring trends in the overstory and understory vegetation resulting from tree mortality (Aldrich and Heller 1969). Large-scale 70-mm color and CIR photography is a feasible method to measure tree losses and monitor change in a sampling framework. For example, the Northern Region (R-1) of the USDA Forest Service uses 1:2,400 color photographs to determine yearly mortality rates in deriving growth and yield estimates.[4]

Forest diseases are not as easily detected and evaluated as insect damage. There are three major reasons for this: it takes a long time for visible symptoms of disease to show up, symptoms are usually not uniform over the stand or forest, and most disease symptoms are far more subtle than insect damage. Therefore, not all forest diseases can be detected on aerial photographs. Those that are detectable with some degree of success are dwarf mis-

[4]*Conversation with D. A. Hamilton, USDA Forest Service, Forest Science Laboratory, Moscow, Idaho.*

tletoe (*Phoradendron* sp.), Dutch elm disease (*Ceratostomella ulmi* (Schwarz)), and oak wilt (Meyer and French 1967, Ulliman and French 1977), basal canker of white pine (Houston 1972), ash dieback (Croxton 1966), *Fomes annosus* (Fr.) Cke (Murtha and Kippen 1969), sulfur dioxide damage (Murtha 1973), and ozone damage (Wert 1969). Large scales of color and CIR film (1:1,584) are needed to assess the degree of damage, whereas 1:8,000-1:16,000 scales of CIR can be helpful in defining and delineating the boundaries of the disease. Again, 70-mm color and CIR photography used as a sampling tool within susceptible types can be useful in damage assessments (Lessard and Wilson 1977, Rush et al. 1977).

Disturbances to the vegetative cover caused by windstorm, flood, fire, or activities of man are relatively easy to detect on conventional aerial photography. Detection and measurement of the change, however, depends on having photography available for two points in time—a base year from which changes are to be measured and current photography. However, photographic coverage often is not available or too expensive to obtain. This and several technical problems make conventional photography difficult to use for change detection. According to Shepard (1964), there are five problems inherent with conventional photography for change detection: (1) noncoincidence of sequential flights; (2) differences in shadow direction on sequential flights; (3) clouds targeted as change; (4) seasonal differences in vegetation indicated as change; and (5) the requirement to handle different film sizes, types, and scales. Landsat MSS data collected from the same or nearly the same sun synchronous orbit at 9-day intervals would avoid some of these problems. This will be discussed in another section of this review. Conventional applications of medium-scale aerial photography for land use and cover-type mapping are well documented in text books (Spurr 1960, Avery 1977).

Nonvegetative cover classification.—Nonvegetative cover includes surface water and soils. The characteristics of lakes and streams and techniques for recreation inventories of mountain lakes are described by Herrington and Tocher (1967). To map the presence of water, CIR and IR films are preferred. Water absorbs IR radiation causing water pictured on IR films to be black and on CIR film to be varying shades of blue. The shade of blue representing water on CIR film is dependent on water depth, sedimentation, and other pollutants.

Probably one of the most effective and economical methods to detect small quantities of oil on water is photography in the near UV region (American Society of Photogrammetry 1975). Fast BW film with a Wratten 18A (W-18A) UV transmitting filter produces photography of the reflected UV energy. However, because of severe degradation by atmospheric haze, this film-filter combination should be flown below 1,000 m and only on clear days. The method is inexpensive and can be used with a 35-mm camera.

Standard BW medium-scale aerial photographs have been used in soils mapping since the mid 1930's. The photographs are used to relate different soils to different landscapes with the photographs providing information to draw soil boundaries. In this way, aerial photographs increase mapping rates and improve map accuracies. Current procedures used in national soil surveys are given in a Soil Conservation Service handbook (U.S. Department of Agriculture, Soil Conservation Service 1966); however, differences in color and tone of adjoining photos, and sometimes within a photo, caused so much confusion that color was not helpful. A more recent study by the Agricultural Research Service (U.S. Department of Agriculture, Agricultural Research Service 1975) in Texas, however, indicates that color and CIR photographs increase mapping rates and cartographical details, and the quality of maps was improved when compared with maps made from BW photography.

Mapping soils directly from aerial photographs has met with only limited success and then only in areas of low vegetative cover. Bare soils, according to Hunter and Bird (1970), have maximum reflectance variation in the 0.6-0.7 μm (red) portion of the EMS. Also, IR photographs give increased contrast between wet and dry soils and are superior for drainage maps. A combination of normal color film and IR film would appear to be best for soil-related information.

Small-Scale Aerial and Space Photography

The most important advance in the state-of-the-art in conventional photointerpretation during the last 15 years resulted from the advent of high altitude and space photography (9,150-24,390 m and over 242 km, respectively). For the greatest part, these advances were made possibly by greatly improved CIR films (CIR 2443 and CIR SO-127) which can penetrate the haze in the earth's atmosphere from both aircraft and space platforms. When used with haze penetrating filters, high definition BW and normal color films will also increase the interpreter's range of capabilities—if the photography is available or if it can be flown within budget restrictions. Small photographic scales provide essentially the same information obtained on medium-scale aerial photographs with only a slight decrease in accuracy (Ulliman and Meyer 1971). A major problem to be overcome with mapping on small scales is the limitation in legend recognition levels that can be used—the legend must

be less complex and delineations must be for larger minimum areas. Often features can be interpreted but, because they are too small, cannot be displayed on a map and are difficult to locate in the field (Marshall and Meyer 1978).

Vegetative cover classification.—Nielson and Wightman (1971) found that 1:160,000 CIR photographs were suitable for broad forest classifications and mapping in Canada. They found that differences between coniferous and deciduous species were striking and some further classification within these broad groups was possible (i.e., some species associations and individual species could be separated). The amount of information provided was sufficient to revise 1:15,840 scale forest-type maps. In a separate and unrelated study in Manitoba, Thie (1972) mapped an area of 6,000 square miles (15,553 km^2) on 1:60,000 and 1:100,000 BW imagery. This seemingly impossible task was accomplished in less than 1 man-year. The cost of large-scale mapping from 1:114,000 CIR was one-half the cost of mapping from conventional 1:15,000 BW photographs (Kirby and Eck 1977).

Range plant communities can be classified on both Skylab S190B color photographs and high altitude CIR photographs to the regional level of ECOCLASS (Daubenmire 1952) with accuracies acceptable for stratified inventory sampling designs (Francis and Driscoll 1976). Regional level classes (grassland and conifer) were correct over 90% of the time, and deciduous (aspen) was correct 80% of the time. Conifer and deciduous class accuracies were dependent on the date of photography, scale, and film type, whereas, grassland was less dependent on these variables. To stratify series-level plant communities, high-altitude CIR film was acceptable only if some classes were combined. The authors concluded that topographic slope and aspect, mountain shadows, ectones, season, and class-mixing adversely affect interpretation of plant communities in the Rocky Mountains.

The mapping of marsh, wetland, and aquatic categories of vegetated and nonvegetated cover on high-altitude aerial and space photographs has been documented in recent literature. On Skylab S190B photographs, visual interpretations resulted in distinguishing 10 vegetation and land use categories with 75-99% accuracies (Klemas et al. 1975). Forest, wetlands, water, and agriculture were classified almost without error. Three separate saltmarsh grass species were separated as were bare soils, sand, cropland, bare mud, and water. Using Skylab S190A photographs, Anderson et al. (1975) were able to accurately classify wetland types, delineate freshwater marshes, and make detailed analyses of drainage patterns.

Nonvegetative cover classification.—The use of high-altitude photography for soils mapping may someday replace current methods using medium scales. For instance, in Minnesota 1:90,000 BW photography has been acquired to use in statewide soil surveys to compile generalized soils maps (Rust et al. 1976). The authors report that the mapping rate was one township per day. Geomorphic regions were used to identify and isolate distinctive parent materials and topography on the photographs. Because information in high-definition BW photography is nearly the same as in conventional photography, it seems possible that these small-scale photographs can be used as a manual procedure for soils mapping with cost savings.

Despite efforts to dehumanize photographic interpretation, the human eye and brain still provide the best interpretation of aerial photographs. The technology of microdensitometry, however, if interfaced with the human brain, may increase the speed of classification and mapping processes in the future.

Interpretation by Film Density

Microdensitometry, or the measurement of optical film density and spatial characteristics of film emulsions, had its roots in the film manufacturing industry (Derr 1960). The application of microdensitometry to wildland resource inventory grew out of attempts by military and private research and development sectors to screen aerial reconnaissance films for military targets using pattern recognition techniques. Earliest attempts to digitize photographic transparencies by optical density specifically for resource inventories were done in the early 1960's (Langley 1965, Doverspike et al. 1965). These early works emphasized separating forest land from nonforest land and mapping forest to establish a base for forest inventories.

Microdensitometers in the early 1960's were slow (170-1,400 μm per second) and the output was usually on paper charts. Today, horizontal-stage automatic-scanning microdensitometers can scan at a rate exceeding 60,000 μm per second. A typical scan of a 9- by 9-inch (23- by 23-cm) aerial photograph with a scan line every millimeter would take 19 minutes to complete. A color transparency with three dye layers (red, green, and blue sensitive) requires three scans or about 1 hour to be completely digitized, recorded on computer-compatible tape, and ready for use in digital image analysis systems. The most useful digitized photographic data will be acquired from small-scale photography. Smaller scales cover larger ground areas, have fewer problems with image distortions, and result in a lower cost per acre for mapped

information. With some additional correction algorithms, image processing software developed for supervised and unsupervised classification of Landsat data can be used with digitized photographic data.

Forestry-related studies.—Several research studies were completed during the early 1970's using a Photometric Data System (PDS), microdensitometer (now Perkin-Elmer) and its companion operating system (Aldrich et al. 1970, Norick and Wilkes 1971, Greentree and Aldrich 1971, Aldrich et al. 1976). These research studies showed that optical density could be used to differentiate between many forest and nonforest land classes. Using Apollo 9 CIR transparencies (1:2,400,000), 13 land use classes could be separated; however, forest types could not be distinguished on density alone. The data suggested that it may be possible to develop signatures for forest types and other land-use classes using a combination of nine variables including density, density differences, and density ratios. It was shown, for a limited area, that film densities could be used with computer-assisted image analysis to separate land use and forest classes. For example, on Skylab S190B color photographs (1:500,000 scale), forest land was classified correctly over 80% of the time but with a 30% commission error. The implications are that forest cover and other land cover types may be estimated by sampling digitized data from future satellite coverage if high resolution CIR film is used and if a classification system is designed that is based on the land cover rather than the intended or current use.

Range-related studies.—Research in the application of microdensitometry to plant identification and yield studies has shown some limited success. In range studies image density differences in CIR aerial photos discriminated individual shrub and tree species of a pinyon-juniper plant community (Driscoll et al. 1974). In addition, image density was used successfully to identify six general plant communities: ponderosa pine, spruce-fir, aspen, big sagebrush, native grasslands, and seeded grasslands. However, there was no attempt to use signatures in computer-assisted classification. Von Steen et al. (1969) found a statistically significant relationship between certain preharvest yield indicators and densities of aerial CIR film. Although this was an agriculture study, the results suggest that in addition to classifying range species and types, optical density estimators may be developed for predicting productivity of range sites.

Unresolved problems.—Results of these forestry- and range-related experiments have been encouraging; however, much research is needed to resolve such questions as the best season and scale of photography as well as to improve feasibility by overcoming photographic variability for time of day, date, and atmospheric conditions. As Coggeshall and Hoffer (1973) stated, "although CIR aerial photographs would be cheaper and easier to acquire than aircraft scanner data, and photographs are easily interpreted manually, the narrower dynamic range of the film, the illumination problems within the photographic set, and the limitation to only three channels of data (red, blue, and green and thus only three dimensions in the computer classifier) seem to pose serious limitations to photo density analysis by ADP techniques—computer assisted image analysis—developed for MSS data."

The two largest problems standing in the way of relating film brightness contained in the three layers of color film to physical properties of a scene seem to be atmospheric interference and film exposure variables. Relatively small changes in sun angle and haze level have been found to substantially reduce classification accuracy using remotely sensed data (Potter and Shelton 1974). One way of reducing the effects of these variables is to use a ratio display method for image brightness variations (i.e., image brightness variations are expressed in the form of relative values or ratios) (Piech et al. 1977). This ratio display method was an effective and accurate approach to interpretation of spectral brightness differences contained in color film. Using the technique, metal, water, pavement, soil, cultivated fields (light vegetation), and vegetation (dark forest areas) were classified with an accuracy of 97% on 1:100,000 scale imagery.

Another approach to atmospheric interference and film exposure variability is through the use of sensitometric analysis. Although sensitometry will be more difficult to implement, this procedure should, in the long run, reduce the problem of diversity between color and CIR photographs taken by a variety of cameras, filters, and film emulsions under different lighting and atmospheric conditions. This approach will require an accurate and reliable sensitometry program—a capability of calibrating film optical density against effective exposure (Dana 1973). Research in this technology should continue while methods such as ratio display of brightness variations are implemented in operational studies.

INTERPRETIVE INFORMATION FOR SPECIFIC APPLICATIONS

Interpretive information is collected to monitor environmental disturbances, trends in wildlife habitat, and geologic hazards, and to chart geologic

structures and locate and assess archaeological finds.

Detecting environmental disturbances.—The impact of natural phenomena and human activity upon the vegetative, soil, and water resources can be monitored using aerial photography. Sometimes aerial photography can be used as a followup to verify and describe phenomena detected by non-photographic remote sensors. This would be particularly cost beneficial if Landsat MSS data were used to screen an area for suspected anomalies. The choise of methods to use in a surveillance system will depend on cost, the amount of detail needed, and availability of photographs, Landsat data, maps, and equipment.

To determine the human impact on roadway environments, an inventory could be made using ground techniques or one of two aerial photo techniques (Potter and Wagar 1971). If the view from the road is important, then a ground surveillance technique is appropriate. If, however, the need is to determine the location of existing powerlines and manmade developments, then an aerial photographic technique can be quite adequate. CIR and color films have major advantages in assessing human impacts because of the increased differentiation they provide among small variations in the ground objects. However, the added cost is not likely to be justified unless the photographs are already available.

Tree condition within municipal limits or within high value areas such as campsites or parks may be monitored on aerial photographs. For example, trees affected by smog can be detected on 1:8,000 color film but to rate the damage, a 1:1,584 scale is needed (Wert et al. 1970). The timing of photography is important to accurately assess the damage. In southern California, December was the best month for assessing damage to ponderosa pine needles. The films and scales required for other more apparent tree damage symptoms were discussed under Classification and Mapping in this review. Also, Murtha (1969) has put together a bibliography for interpretation of forest damage, which is close to the state-of-the-art. He has also assessed vegetation damage problems and makes appropriate recommendations for solutions (Murtha 1976). An overview of techniques for forest insect damage surveys is also given by Heller (1974).

Remote sensing of the impact of grazing animals on stream and meadow ecosystems has been reported by Hayes (1976). In his technique for appraising grazing impact, Hayes used a 70-mm camera and CIR film. He found that 1:2,000 to 1:8,000 photographs will provide resource analysts with a method for observing the influence of management systems on stream-meadow complexes. The photographs provide a vegetal stratification and identification and a base for further observation of vegetative change—range condition and trends. Stream channel stability and alterations can also be monitored. CIR photos at 1:600 to 1:1,000 scale were an aid in detecting differences between grazed and ungrazed areas within a single vegetative complex. Fecal matter could be recognized on 1:2,000 scale photography.

Wildlife habitat.—To monitor wildlife habitat trends and related vegetative and hydrologic changes, Scheierl and Meyer (1977) found a 35-mm photography system beneficial. They used both CIR and color at a 1:8,000 scale. Color film was most useful for aquatic plant detection, species differentiation, and enhancement of shrub differentiation. Color combined with the CIR enabled detection and differentiation of upland vegetation with optimum results. They recommend using plant indicators for establishing the optimum time of year for photography.

In another closely related study, Greentree and Aldrich (1976) found that 70-mm photography was useful for monitoring stream trout habitat conditions. They found that most characteristics of trout streams are visible and easily described directly on the photographs. Habitats supporting trout stream insect production can potentially be evaluated using the photographs as a base from which to sample and collect the biological data. The best overall scale and film for evaluating streambank conditions is color at a 1:1,584 scale. CIR film is best for evaluating low grassy areas with undercut banks and where healthy aquatic vegetation is found.

Geologic structure and hazards.—Geological hazards such as damage resulting from earthquakes, including seismic seawaves along coastal areas, landslides in areas of unstable slopes, and subsidence and flowage of surface materials in areas underlain by sands and clays in various stages of water saturation are interpreted from aerial photography (Pestrong 1971). The author also points out hazards associated with surface water, including flooding along streams and rivers, erosion and gullying of certain slopes, and standing water hazards in areas of poor drainage, can be detected on aerial photographs. Because of the economic consideration, however, the principal film used for interpretation is BW. He goes on to say that CIR photographs would be more useful because of the subtle shades of hue and saturation that are important in addition to form and shape. The CIR will show landslides disrupting drainage and vegetation more clearly than other films.

According to Hunter and Bird (1970), IR photographs are particularly useful in geological interpretations because surface configuration and textural patterns on exposed bedrock are emphasized by shadows and moisture in depressions. However, to find outcrops underneath vegetation requires 1:4,000 color taken under an overcast sky (Myers 1975).

The application of remote sensing including aerial photographs, Landsat, thermal scanners, and radar for landslide hazard interpretation is covered by Gagnon (1975). Hazards are defined by Gagnon as slips, slumps, and clayey outflow (liquefaction). Slip and slump are controlled by slope, and clayey outflow is affected by ground water table, saturation, drainage, infiltration, and vibration. Color photographs have advantages for soil color and identification, and for detection of thin organic material, infiltration lines, and sand-silt cover. BW IR is important for water and soil moisture analyses. For example, ground water table, saturation zones, high water content surface materials, seepage lines, surface drainage, saturating water bodies, and infiltration lines must be checked with this imagery. CIR photographs can provide surface drainage, infiltration lines, and ground water mainly through vegetation analysis. However, CIR does not add significantly to the information available on BW IR.

Archaeological applications.—Archaeology, probably more than any other science, fully utilizes aerial photographs to interpret sites based primarily on associations. Detection and evaluation of most archaeological sites is made possible by recognizing certain factors in obtaining photographic data. One of these factors is that drier seasons of the year are preferred over wetter periods because the loss or retention of moisture by various soils provides more striking tonal contrasts (Lyons and Avery 1977). In areas of high humidity, aerial photography for archaeological application should be done during the leafless period. However, there really is no single period of the year that is best for all forms of archaeology. If shadows are important, photographs should be taken in the early morning or late afternoon, when the sun is low. Midday sun is best to minimize shadows, to gain the best illumination of terrain features, and for good color rendition.

The film type and scale of photography most useful for archaeology vary. However, there is agreement that color is better than BW for most work and that CIR is preferred for delineating subsurface detail such as shallow buried foundations (Lyons and Avery 1977). Both color and CIR are better than BW for detecting soil marks and certain crop or plant marks. Since BW IR has been found useful for locating buried pipelines, it should be investigated for archaeology. According to Lyons and Avery, 1:10,000-1:20,000 scales have been successful; however, the literature indicates that 1:3,000 to 1:10,000 scales are preferred. Multiband photographs are preferred by Whittlesey (1972) because they increase the capability to detect archaeological sites by comparing various film/filter combinations simultaneously for the same area.

MEASUREMENTS OF RESOURCE PARAMETERS

Direct field measurement is the only substitute for a stereoscopic pair of vertical aerial photographs to measure parameters of the forest and other wildland resources. Combining field and photo estimates can be 6-15 times more efficient in estimating commercial forest land area than is using field plots alone (MacLean 1963). Volumes obtained by photo measurements and photo volume tables reduce field survey time about 60% (Moessner 1963) and double sampling for stratification provides estimates of total volume twice as efficiently as does simple field plot sampling (MacLean 1972). Much of what we know today about photo measurements is the result of work by early forest photogrammetrists such as Moessner (1949, 1960, 1961), Rogers (1946, 1947), and Spurr (1945, 1948). Avery (1977) and Spurr (1960) give complete instructions on how to use aerial photographs to measure area, height, crown closure, and crown diameter, and how to relate these measurements to stand size, site, and volumes. Publications with specific applications of aerial photographic measurements are annotated by Nielson (1971).

The mensurational aspects of resources, other than forests, are generally restricted to determining areal extent of delineated soils, landform, and plant communities. The scale of aerial photographs and topographic relief have a great affect on the accuracy of these measurements.

Mensuration.—Improvements in photographic techniques for mensuration have come by way of larger scale photography, more efficient sampling designs, and improved measurement instruments; the basic concepts and techniques have remained the same. For example, large-scale, 70-mm photography using color, CIR, and BW positive transparencies, contact prints, and enlargements opened up a new information source for resource inventories and resource monitoring. Tests of large-scale sampling photographs as early as 1962 (Sayn-Wittgenstein 1962) showed that they would play an important role in future forest surveys. He cautioned, however, that before reliable measure-

ments could be made, certain important problems needed to be solved, not the least of which was scale variation. One way of handling the scale problem was by using a fixed air-base and two cameras from a helicopter (Lyon 1967). With a fixed air-base the flying height above ground could be calculated and mean height measurements made within ±3 feet (0.91 m). The cost was only 15% of the standard survey cost for rather remote areas of British Columbia.

Another way to overcome the problem of scale variation inherent in large-scale photography was developed by the Canadian Forestry Service. This development was a radar altimeter specifically to fit the needs of forestry (Nielson 1974).During the large-scale photographic mission,the altitude above ground is printed directly on the film. Nielson (1974) reports that vegetation is completely penetrated and the accuracy of flying heights is within ±1% of the actual altitude. In typical mixed conifer and hardwood stands in Canada, tree heights were made within 3.5 feet (1.07 m) and crown diameters within 2 feet (0.61 m) (Kippin and Sayn-Wittgenstein 1964). No more than 4% of the trees were missed. This radar system is now available commercially.

For timber volume estimates, large-scale photographs require that the stand approach be abandoned in favor of precise examination of samples of individual trees (Aldred and Kippin 1967). By examining individual trees and measuring the variables of total height, crown width, crown area, proportion of tree crown overlapped by crown of another tree, and other expressions of a tree's position in relation to its neighbors, the contributions of each toward reducing the residual sums of squares was determined in a stepwise regression (Sayn-Wittgenstein and Aldred 1967). The most useful variables were direct measurements of the trees. Expressions of position of a tree in relation to its neighbors—the crowding or competition factor—were less important.

When large-scale 70-mm sampling photography is used in tropical forests, the specifications are somewhat different than photography in the northern boreal forests. Aldred (1976) recommends that the most accurate measurements are made on positive color film transparencies at scales of 1:2,000-1:4,000 taken under an overcast sky. These same specifications are optimal for tree species identification except that larger scales would probably produce the most precise results, although at probably an unacceptable cost.

In recent years there have been two large area operational timber inventory trials using large-scale aerial photographs—one in Nova Scotia (Bonner 1977) and the other in Alberta (Aldred and Lowe 1978). Both inventories provided the required forest statistics close to specified limits of accuracy. In both examples the photo method was found to be most cost effective when applied to inventories of large, relatively inaccessible areas that sometimes require the use of aircraft for ground access. In Alberta 100-500 plots would be required before the photo method would pay off.

Range inventories require a measure of the cover percent of grasses, forbs, and shrubs. Large-scale aerial color and CIR photographs can be used to measure percent vegetative cover from recognizable species in a significantly shorter time than conventional field methods using larger sample sizes (Tueller et al. 1972). However, the density (number of plants per unit of area) cannot be extracted for most species.

Water measurements.—Herrington and Tocher (1967) describe characteristics of lakes and streams that are measurable on aerial photographs. These measurements are important in recreation inventories of mountain lakes. The depth and quality of water is also important in water resource inventories. According to Helgeson (1970) reasonable increases in the apparent depth or distance penetration of masses of water may be accomplished by sensing the proper region of the EMS. He goes on to say that properly displaying the remote sensing record will enhance the use of the dynamic density range of the material. He describes and recommends a multilayer photographic material—either bicolor or tricolor—in bands properly selected to take advantage of spectral absorption and scattering properties of water. The choice of bands should be based on the spectral differentiation required for bottom detail.

Water quality indicators are also important in classifying lakes and streams. Bartolucci et al. (1977) found by in situ measurements that differences between turbid and clear water are most apparent in the 0.6- to 0.9-μm region of the spectum or within the sensitivity of CIR film. They also found that river bottom reflectance characteristics have no influence on the water reflectance characteristics when the water is over 30 cm deep. Schutz and Van Domelan (1975) present several theoretical equations to use in computing and describing physical relationships, bottom effects, effects of oil slicks, turbidity, and algae. They describe how backscatter of different wavelengths change with the type of material in the water. Thus, each type of material has a unique spectral backscatter "fingerprint" which allows them to be identified. For instance, they have developed curves to "fingerprint" distilled water, clear Lake Superior water, taconite rock flour, moderate red clay, and heavy algae. These and similar signatures can be useful in application of both aircraft and Landsat images for classifying

lakes. There are pitfalls, however, in applying signatures beyond the immediate area for which they were developed.

Sand movements.—Movement of sand is important in managing coastal zones. Vegetation is the best know precipitator of sand accumulation. Aerial IR photography has been used to detect the topographic changes in vegetation-induced sand dunes of the North Carolina outer banks (Stembridge 1978). The high IR reflectance produced by the mutual interdependence of precipitator dune vegetation and windblown sand accumulation makes it possible to predict dune growth and deflation pattern in vegetated coastal dune systems.

OBSERVATIONS AND COUNTS OF OCCURRENCES

Observations required by USDA Forest Service users of remote sensing data include buildings and structures, water structures, transportation, recreation, and wildlife. With the exception of recreation and wildlife uses, it is highly unlikely that special-purpose remote sensing will ever be justified. As recreational and wildlife management activities increase, however, special-purpose remote sensing may be required to monitor human activities and their effect on the wildland resource and wildlife populations (big game). Other observations will be made from available photography or from aircraft.

Manmade structures and developments.—Studies to determine the accuracy of observations using aerial photography are extremely rare. Most information related to manmade structures and developments must be taken from references to urban and regional surveys of land use and other studies by geographers.

Geographers have found that high-altitude photography (1:120,000) can be used to prepare urban land use maps to a 1-ha minimum (Simpson 1970a). These maps are prepared with 24 different categories and usually to a 4-ha minimum to compare with Landsat data. Simpson (1970a) also says that CIR transparencies are particularly useful for urban land use identification, delineations, and for urban change detection.

In Los Angeles 1:60,000 scale aerial photography was found useful in urban studies (American Society of Photogrammetry 1975). This scale was most helpful to provide extensive coverage of a city and its immediate surroundings. However, 1:20,000 scales permitted identification of city sections with greater detail and 1:5,000 was most appropriate to study individual properties. Good quality 1:60,000 photographs can be enlarged to 1:20,000 and 1:5,000 without loss of resolution and provide necessary information at the individual property level.

Generally speaking, to detect and evaluate structures and transportation, communication, and utility systems, and to count vehicles and other items within a wildland environment requires photographic resolu-capabilities ranging from 0.3 to 15 m. Although in most instances available photography will be used, CIR will have the greatest utility.

Recreation and wildlife management.—Aerial photographs could be advantageous for both recreation and wildlife census because they capture a scene instantaneously on a piece of film for later study. Ski slopes, parking lots, boats, marinas, and the wakes of boats are discernable even at 1:120,000 scales. However, accurate counts of vehicles and people will require much larger scales. People counts will require at least 1:2,000 scale or 0.1-m resolution. Large-scale 70-mm aerial sampling photography over recreation sites could be useful for monitoring recreation use impact.

Aerial photographs could be used for animal census particularly when the animals group together in the sunlight. However, aerial films see approximately the same scene that the human eye can see. Therefore, if the animals are camouflaged on the ground, they will also be invisible on film. Another limitation is the need for optimum weather and bright sunlight (Parker 1971). This is because deer often seek cover during the middle of the day when picture taking is best.

Probably the best example of the use of aerial photography for animal census is a livestock inventory made in California (Huddleston and Roberts 1968). In this and previous studies, a scale as small as 1:5,000 could be used as a sample with consistently high accuracies. BW film was most acceptable from a cost and effectiveness standpoint. However, color transparency film gave the best accuracy, particularly for identifying the animal type and breed. A W-12 filter used with BW film increased the contrast and haze penetration and darkened the shadows to give a more interpretable image. Huddleston and Roberts (1968) found that the best season for inventories was early spring after the winter rains but before shallow soils dried out and caused vegetation to brown up. The best time of day was a few hours after sunrise and a few hours before sunset, when animals were not seeking shade. However, aerial photographs are limited in that livestock are not detectable under manmade or dense natural covers. Simultaneous ground enumeration must be made to develop corrections for bias in the image counts.

In an unusual application of aerial photography, harp seal pups were found detectable by UV photography (Lavigne 1976). Standard BW film registers only dark-colored adult harp seals on ice. With a special lens and film sensitive to UV rays, white costal pups were detected against the white background. The pup's fur absorbs much of the UV in sunlight. So does the polar bear; however, the arctic fox and hare tend to reflect UV light. Snow and ice also reflect UV. Thus, with the special lens (with UV filter) and film, a pup is registered a black image on a white background.

THE STATE OF REMOTE SENSING APPLICATIONS—NONPHOTOGRAPHIC DATA

The use of data from nonphotographic imaging devices has increased by leaps and bounds during the past 5 years. The advent of Landsat-1 in 1972, the Skylab Earth Resource's Experiment Package (EREP), and Landsat-2 and Landsat-3, has provided investigators with relatively low-cost data. Data are available on computer-compatible tapes and in electronically reconstituted photographic products. At present, MSS data are used more often than any other nonphotographic data for classification and mapping. Thermal and radar data are used less frequently to monitor resource conditions.

CLASSIFICATION AND MAPPING

Both computer-aided and conventional photointerpretation methods are used to analyze data from nonphotographic devices. Computer-aided classification using digital data stored on computer compatible tapes is generally considered the best approach in classification and mapping. Even though the spectral data are relative values and have been affected by atmospheric conditions, data are calibrated (system corrected) when recorded. The digital format provides the user great flexibility in analysis techniques. Photographic products can be made from the recorded data but the products are sometimes degraded to a certain extent in the photographic process. However, digital data often can be processed to enhance edges or scene contrast and to digitally enlarge the data in the photographic product (Rohde et al. 1978). Both computer-aided and conventional interpretation are discussed in the following sections.

Airborne Multispectral Scanner Data

The uses of airborne MSS in wildland resource management have been restricted to a few experimental applications in vegetative cover mapping, detecting disturbances, and nonvegetative cover mapping. From a technical point of view, airborne MSS can provide spectral and spatial resolutions to accurately map wildland resources. However, there are many operational problems still to be solved and costs of data acquisition and analysis must be reduced to be competitive with aerial photography.

Vegetative cover classification.—Early studies in vegetative cover classification using airborne MSS data for forest species discrimination were relatively successful. They usually looked at homogenous plantation-like forests under intensive management where positive results were most likely. One such study was made on an 80-acre (32.4-ha) experimental forest in Michigan (Rohde and Olson 1972). MSS data from six spectral regions between 0.4 and 1.0 μm were used in a computer-aided classification procedure. Coniferous tree species were discriminated from broadleaved trees, and sugar maple, black walnut, black locust, red oak, and white oak were successfully separated from one another. Discrimination between conifers was not as successful although spruce was consistently separated from pine. Overall accuracy, under these ideal conditions, was 85%.

Results of the first attempt to classify and map forest and other land cover classes on a wide area basis under natural conditions were rather discouraging (Weber et al. 1972). However, the test results did provide some leads for further research. For instance, the test indicated a need for an improved algorithm for applying corrections to the MSS data for sun angle and atmospheric interference and an improved sun sensor to measure irradiance during MSS flights. In addition, map quality and accuracy of point locations was poor as a result of uncertainties of aircraft altitude and velocity changes. One bright point from the study was the isolation of four channels of data that were most successful for classifying land cover in the north central Georgia area—the visible red band, two near IR bands, and one thermal band. These bands are very similar to recommendations made by Coggeshall and Hoffer (1973).

Airborne MSS data have been processed to map biomass in shortgrass prairie vegetation (Pearson et al. 1976). Results of image processing of these data were compared with actual ground-measured biomass values taken at the same time. The image processing prediction was 1.15 times the actual biomass with a correlation coefficient of 0.98 for 26 biomass ground truth areas.

Disturbance.—Another application of multispectral data that received a great deal of attention during the late 1960's and early 1970's was detection

of change in physiologic structure of trees under moisture stress (Weber and Olson 1967, Olson and Ward 1968, Olson 1972). Although there is good evidence that physiological changes occur in trees under moisture stress, it has been difficult to show evidence of this on remotely sensed data until after the trees are dead and the foliage has changed color. Bark-beetle-attacked trees are dead or beyond saving (but salvageable) once the tree foliage has turned color. By this time it is usually too late to prevent additional trees from being attacked. Previsual detection of trees under stress would be helpful to forest biologists in controlling the insect and disease outbreaks by silvicultural or other management procedures.

When airborne MSS data were tested for both visual and previsual detection of stress caused by root rot fungus (*Poria weirii*), mountain pine beetles (*Dendroctonus ponderosae* Hopk.), and oxidant air pollution damage, the results were discouraging (Weber and Wear 1970, Weber and Polcyn 1972). Incipient root rot infections in Douglas fir (*Pseudostuga mensiesii* (Mirb) Franco) could not be successfully identified using either multiple-channel processing in the 0.4- to 1.0-μm and 1.0- to 5.5-μm portions of the EMS or single-channel processing in the thermal data channel (8-14 μm). Oxidant-injured ponderosa pine in southern California could be discriminated by condition classes best in the 0.55- to 0.70-μm range of MSS data. However, the range of temperature difference between condition classes was too narrow and the data overlapped too much for accurate classification of thermal data. The greatest benefit MSS scanning could provide forest biologists, according to Weber and Polcyn (1972), would be previsual detection of stress in bark-beetle-infested trees. Working with three spectral bands (0.4-1.0, 1.0-4.5, and 8.2-13.5 μm), they were able to show very little evidence of previsual detection. However, with the availability of simultaneously registered data (not available at the time) covering the entire broad-band width in narrow band increments, large improvements in the results could be expected. At the present time, however, there is no evidence that MSS's are feasible for insect and disease survey.

Nonvegetative cover classification.—Soils mapping from remotely sensed data is most difficult where the land is covered by vegetation. Often a lack of correlation between current vegetation and soil class (Johnson and Sellman 1975) makes soils mapping more difficult. Where the soil is unvegetated, however, classification of soil by remote sensing has been more successful (May and Peterson 1975). Their study compared signatures for several Pennsylvania soils corrected for solar and atmospheric interference with signatures derived from MSS data in supervised and unsupervised computer classification routines. They found that the laboratory-derived signatures could be substituted for MSS signatures with only a slight decrease in accuracy. Computer-derived maps were similar to maps made by field surveys and were in agreement 90% of the time. According to Westin and Frazee (1975), using Landsat photographic data as a background in soils mapping greatly enhances information that can be deduced about hydrology and land use. They also found that color composites were adequate for locating most boundaries between soilscapes.

Special considerations.—Although it is ineffective from a cost standpoint today, MSS data from airborne platforms could provide spectral and spatial resolutions to accurately map wildland resources. Classification accuracy is highly dependent on the number of channels of data used and the portion of the EMS from which the channels are selected. According to Coggeshall and Hoffer (1973) the most cost-effective use of MSS data would be to use no more than five bands of data (over five bands results in very little improvement in classification accuracy at an increased cost) and at least one band should represent each part of the optical spectrum—two visible, one near IR, one middle IR, and one thermal IR. In this way classification accuracies of over 90% can be realized.

Variations within forest land can result in classification errors using MSS data and computer classification procedures, and these errors are difficult to account for. The reliability of feature signatures is dependent on the relationship of each signature to all others in the set (Sadowski and Sarno 1976). Signatures that compete with or statistically overlap neighboring signatures produce low classification performance because a large number of pixels are misclassified. Thus, signatures with small variance and high correlation may have an advantage over signatures with large variances and/or lower correlation. Multiple signatures might be used to characterize nonuniform areas within a feature to produce signatures of smaller variation and improve classification results.

When the spatial resolution of MSS data is degraded from 2 to 64 m^2, the overall classification of MSS data is improved (Sadowski et al. 1978). This improvement is attributed to a reduction in scene variation inherent in the averaging of information over large ground areas. There was 100% increase in the accuracy. This implies that there is substantially better classification performance for more generally defined features and that resource managers should be advised to avoid discriminating features that are too specific when processing MSS data by conventional procedures. Furthermore,

multielement classification rules provide for averaging information over larger areas, which is somewhat analagous to coarsening the resolution. For instance, averaging over nine elements (pixels) could be advantageous to improve the classification of detailed features that may be needed in resource inventories using coarser resolution satellite data.

Landsat Multispectral Scanner Data

Contrary to recommendations derived from airborne MSS studies (Coggeshall and Hoffer 1973), Landsat-1 and Landsat-2 MSS's were designed with four bands: two visible bands (0.5-0.6 μm, green; 0.6-0.7 μm, red) and two near IR (0.7-0.8 and 0.8-1.1 μm). A thermal band was added to Landsat-3 that covers 10.4-12.6 μm of the EMS. After geometric corrections based on U.S. Geological Survey (USGS) 1:24,000 map controls, or their equivalent, the geodetic error of a Landsat image is $<$1.0 pixel (57 m) and the temporal registration error between two images having the same World Reference Frame Numbers is only $<$0.5 pixel (28 m) (National Aeronautics and Space Administration 1978). World Reference Frame Numbers are used in a Landsat Worldwide Reference System (WRS) to locate centers of individual scenes. Reference numbers are defined by intersections of 251 Landsat ground tracks and 248 rows.

Vegetative cover classification.—One of the earliest and most comprehensive studies of Landsat data for land cover classification was conducted by the USDA Forest Service, in cooperation with NASA (Heller 1975). After 24 months of study Heller summarized that Landsat was primarily a source of first level information for multistage inventories of forest and range resources. Aldrich et al. (1975) and Driscoll and Francis (1975) reported that forested land could be separated from nonforest and water regularly with 95% accuracy and that forest and grassland were separable at the regional level of ECOCLASS (Daubenmire 1952) 92-99% of the time. However, when separations at lower levels in classification hierarchies were attempted, the level of accuracy dropped significantly below what was acceptable.

In a study of rangeland classification in southern Idaho, Hironaka et al. (1976) found that sagebrush stands could be separated from cheat grass on spring season imagery because of high reflectance from rapidly growing grasses. Such separation was not possible later in the season. They had only limited success in identifying ranges cleared and reseeded to crested wheat grass, probably a result of low IR reflectance caused by a high percentage of bare ground present in reseeded range. Success in identifying native range types depended on rainfall, amount of vegetative cover, and season of the year. Enlarging Landsat photographic images separated by four or five passes would permit managers to monitor conversion of rangelands to cultivated and irrigated crops and locate and measure the extent and configuration of burns in sagebrush-grass range.

Some of the more advanced techniques for interactive Landsat and photographic data sources were developed for the Large Area Crop Inventory Evaluation (LACIE), a joint project of the USDA, NASA, and the National Oceanic and Atmospheric Administration (NOAA). One development, known as procedure 1, was applied to rangeland classification (Reeves 1978). Procedure 1 is a computer-aided processing technique developed to optimize ADP and to minimize analyst processing time. The procedure uses a 117-line (row) by 196-picture element (pixel column) image area of Landsat digital data called segments. Aircraft data are required and classification success depends on the assumption that rangeland, nonrangeland, forest, nonforest, and water can be differentiated on aircraft photos with no significant error. It also assumes that shortgrass prairie, saltgrass, hardwood, and softwood can be differentiated on aircraft imagery with no significant error. The aircraft photos are used to establish probability of correct classification and to evaluate the Landsat classification results. The procedure produced accurate rangeland classifications, but short prairie grass and saltgrass could not be differentiated on the aerial photographs; therefore, these classes could not be separated in the procedure.

The use of Landsat MSS data in computer-assisted classification of wetlands is not as well documented as wetland mapping by conventional photointerpretation. This could be because many wetland areas are too small or too narrow for detection by Landsat or it may be because water absorbs IR and, therefore, is in conflict with IR reflected from vegetation. Nevertheless, there has been some success using Landsat data for general classifications, boundary definition, and monitoring human impact on wetlands (Anderson et al. 1975). In coastal zones, Klemas et al. (1975) found that a human-assisted approach to automated classification correctly classified ten categories of vegetation and land use with over 80% accuracy. Later, Klemas and Bartlett (1977) found that conventional computer-training techniques using relative radiance values for the different categories gave slightly better results than training signatures developed from in situ measurements of target radiance (85% versus 81%). They also found that variability of spectral reflectance in wetland areas is symptomatic of physical characteristics of the cover types (i.e., time

elapsed since tidal inundation of mud, plant height, and growth form).

Excellent treatments of the processes followed in computer-aided vegetative cover classification using Landsat digital data are provided by Hoffer and Fleming (1978) and Rohde (1978a).

Generally speaking, the accuracy of land cover classification is improved when two or more Landsat image dates are combined. However, very careful selection of the image dates is important. For example, in Canada, Kalensky (1974) used 12 channels of data representing 3 different dates (4 channels each date) and compared the classification results with 4 channels recorded on 1 date. The accuracy for the single-date classification ranged from 68% to 81%. For the multidate maps the accuracy increased to over 83% for agriculture, coniferous forest, and deciduous forest classes. In another, related study in the North Carolina coastal region, Williams and Haver (1976) had similar results, combining data for two Landsat scenes (winter and summer). The two scenes were analyzed individually, registered, and merged into eight channels of data to take advantage of temporal changes in the forest canopy. The best results were obtained from the combined data. Delineations of hardwood and pine categories and clearcut acreages were over 94% correct. However, the best separation of hardwood and pine was on winter data. Summer data allowed separation of pine into categories based on crown closure. Multidate images must be accurately registered pixel to pixel or many changes will be missed and some will be false calls. Accurate registration is the product of geometric corrections and must be within ±0.5 pixel to be effective. The new process for geometrically correcting Landsat data tapes at Earth Resources Observation Systems (EROS) Data Center (EDC) should fulfill this requirement when fully operational.

Large-area demonstrations of vegetative cover classifications.—Good quality photographic data produced electronically from Landsat computer-compatible tapes can be used with conventional photographic interpretation in large-area resource inventories. For example, a random-systematic double sample was used to estimate deciduous and coniferous forest area in nine counties in northern Virginia coastal plain counties (Aldrich and Greentree 1977). For deciduous and coniferous areas the sampling errors were 3.7% and 6.7%, respectively (at the 0.67 probability level). Total forest area was <1% different from the Forest Survey[5] estimate. Although the Landsat technique resulted in sampling errors 2-3.5 times larger than sampling errors for an operational inventory, with improved techniques for electronic enhancement and geometrically correcting Landsat photographic products such as those now available at EDC, these errors could be reduced considerably.

Recent literature cites several examples of the application of Landsat-1 and Landsat-2 data to land classification and forest mapping on large-area inventories using computer-aided techniques (Dodge and Bryant 1976, Krebs and Hoffer 1976, Roberts and Merritt 1977, Oregon State Department of Forestry 1978, Harding and Scott 1978). These examples have several things in common: (1) Landsat MSS data were used to stratify land classes by vegetative types, (2) computer-assisted classification was used in preference to conventional photographic interpretation, and (3) acreages of forest land and vegetation types were computed. Landsat classification accuracies for both forest area and forest type statistics were usually based on comparisons with Forest Survey Statistics for the most recent inventory. In most instances, these estimates were within ±10% for forest area and within ±25% for forest type.

A resource inventory in the San Juan National Forest in Colorado produced a forest cover map made from Landsat MSS data in combination with high-altitude CIR photographs and ground truth (Krebs and Hoffer 1976). Geomorphic features were manually interpreted and mapped from Landsat photographic data. Slope and aspect were interpolated from elevational data on Defense Mapping Agency (DMA) tapes of 1:250,000 USGS topographic map sheets. The topographic data were developed into 64-m grid cells and overlayed onto the Landsat data classified by a modified clustering technique using computer-aided classification. The modified clustering technique required less computer time to develop training statistics and produced statistics yielding higher classification performance. Vegetation-type maps within certain topographic positions could be produced with an accuracy of 84% at generalized levels (broad) and 80% at the community level (narrow). USDA Forest Service personnel in local management and land use planning activities considered the map as good or better than maps produced by conventional photographic interpretation techniques at a much higher cost.

In the conduct of national renewable resource inventories it is important to have accurate area estimates of forest land and forest types. Roberts and Merritt (1977) using a 17% sample of Landsat-2 data for a nine-county area in the northern coastal plain of Virginia and a combination of unsuper-

[5]The Forest Survey was authorized by provisions of the McSweeney-McNary Act of May 22, 1928, as amended by the Resources Planning Act of 1974. Forest Survey units are now known as Renewable Resources Evaluation Units and are organizationally under the Division of Forest Resources Economic Research, USDA Forest Service.

vised clustering and supervised classification algorithms, produced a forest area estimate less than 1% different from the Forest Survey. By individual counties the area differences ranged from 3% to 21%. Water was classified correctly 98% of the time. There was no reliable comparison for conifer and hardwood acreages. However, these and similar results using manual interpretation techniques indicate possibilities for Landsat data as first-level information in national, regional, and state renewable resource inventories.

A demonstration project conducted by the Oregon State Department of Forestry (1978) utilized Landsat for forest condition mapping and a forest volume inventory in Douglas County, Oregon. Products were color-coded maps produced at 1:125,000 with 9 generalized vegetation classes and at 1:62,500 with 24 vegetative treatment classes. Acreages were summarized by treatment opportunity group—conifer, conifer/hardwood, hardwood, hardwood/conifer, nonstocked forest, nonstocked other, and water by ownerships. Summaries were made of acreages by treatment opportunity groups, crown closure, and tree diameter classes for ownerships. Volume and standard errors were based on photo/ground estimates weighted by Landsat defined selection probabilities but without corrections. Volumes and areas from conventional inventories by government agencies and industry were compared with the Landsat estimates. The general conclusion was that statistics generated by the project were not usable and that additional refinement is needed before remote sensing statistics are reliable and can be used by management foresters.

A similar inventory was conducted in the State of Washington by the Department of Natural Resources but for a much larger area (Harding and Scott 1978). Nine Landsat scenes were selected to cover the entire western Washington project area and supplied the data base from which sample plots were located. Sampling was reduced to a minimum by stratification with Landsat data and the use of a multistage sampling design. Landsat coordinates of selected sample pixels were used to compute Washington state plane coordinates which were, in turn, used to plot secondary sample units on orthophotos and maps and eventually aerial photographs. A high degree of accuracy in relating pixels to ground locations was essential to the overall accuracy of the inventory. The secondary samples were transferred to aerial photos to an accuracy of 100 feet (30.50 m) with one-half the samples within ± 50 feet (15.25 m). However, since the equation for transforming Landsat coordinates to Washington state plane coordinates was accurate to only ± 1 pixel, the overall accuracy was not better than this. The study provided basal area by ownership class within ± 10% (0.95 probability level). In summary, the Landsat inventory process could be cost effective when and if the development work has been completed. Landsat can supply accurate data and there are adequate computer systems to handle the data, but software and procedures must be refined. Further work is required to make the Landsat inventory process both operational and competitive with existing systems.

During the period of 1976 through 1978, the Nationwide Forestry Application Program (NFAP) at NASA's Lyndon B. Johnson Space Center (JSC), extended ADP technology to intermediate-sized applications in ten ecosystems throughout the continental United States and Alaska.[6] The Ten Ecosystem Study was an ADP feasibility study using Landsat data, supporting aircraft imagery, and ancillary information for inventorying acreage of forest, grassland, and water. The same procedures were followed on each site and all image processing was done on a General Electric 100 interactive image processor. In summary, the overall accuracy of classification was about 80% ±5% (0.90 probability level). The consistency of classification, however, was not that good with a range of 35-95%. On sites with steep terrain, there were extensive areas of nonclassified data. Where brush was less than 50% of the cover, a pixel was classified as grass or bare ground depending on the amount of grass cover. Problems such as the latter will make it difficult to use Landsat data for rangeland inventories. When data from two dates were combined to take advantage of temporal information, classification accuracies were poorer than with either single date classification.

A good review of several forest and rangeland applications of satellite data in multistage and multiphase sampling designs is given by Rohde (1978b). Included are timber volume inventories, range inventory, inventory of wildland vegetation, inventory of rangeland converted to cropland, and inventory of strip mine disturbances.

Disturbance.—Attempts to classify and delineate areas of vegetation under stress met with mixed results. Rohde and Moore (1974) claimed they could delineate moderate and heavy defoliation caused by gypsy moths in Pennsylvania. Heller (1975) reported eucalyptus killed by a freeze in the Berkeley Hills area of the San Francisco Bay region in California could be detected on registered Landsat images for two dates (before and after). Weber et al. (1975) reported no success in detecting bark-beetle-killed trees in the Black Hills of South Dakota. However, heavy sulfur dioxide damage to

[6] *Information furnished at the Ten Ecosystem final review, September 20, 1978, at JSC, NASA, Houston, Texas.*

forest vegetation was detected and mapped by Murtha (1973) near Wawa, Ontario. Using photometric methods and ground estimates of defoliation from known sites, a map was produced for northeastern Pennsylvania indicating relative stress caused by gypsy moths (Talerico et al. 1977). From these results and still others, it seems entirely possible to map disturbances caused by unusual stress conditions occurring over broad areas. This is particularly true if multidate images and computer-assisted techniques are used to take benefit of spectral differences in first generation spectral data on computer-compatible tapes. However, unless one knows of the existence of stress conditions beforehand, or unless extremely sensitive and efficient techniques can be developed for multidate temporal data registration and analysis, there seems very little promise for Landsat data to systematically monitor the wildland resource base for vegetation stress.

Probably the greatest success in change detection using Landsat data will be realized when monitoring the vegetative cover for disturbances caused by disasters such as windstorm, flood, and fire or when monitoring human activities (Robinove 1975). For instance, acreages for clearcut and uncut mature timber determined from Landsat imagery were found to be reliable (Lee 1975, Lee et al. 1977). Using multidate imagery, burned-over areas and changes in the logged-over area were accurately isolated (Williams and Haver 1976). Aldrich (1975), comparing 1:63,360 scale photographic data and Landsat photographic data (1:1,000,000) detected 80% of all disturbances occurring over a 6-year period in one Georgia county. These included harvesting and silvicultural treatments, land clearing, regeneration, and others. In the Black Hills of South Dakota, Weber et al. (1975) easily detected the path of a tornado through ponderosa-pine-dominated forest land. From these studies it is concluded that to detect a change in the vegetative cover it must be 2 acres (0.8 ha) or larger in size and that the contrast with neighboring classes must be maximized by careful selection of temporal data for at least two dates.

In another stress-related application, rangeland might be monitored on temporal Landsat data using associated ancillary information during the spring and summer for (1) water quality and quantity; (2) location of high use areas, climatic patterns, and to establish base data for certain periods of a grazing season; and (3) environmental conditions to make yearly assessments of the changes within the rangeland environment (DeGloria et al. 1975). The information could be used to establish and document regular patterns of rangeland changes. Both conventional interpretation and computer-assisted techniques might be used to quantify changes in areal extent and/or onsite phenological changes in sensitive rangeland areas. However, current levels of accuracy in automated classification are not high enough and increased accuracy is needed in selecting proper Landsat dates, training sets, and the appropriate classification scheme.

Nonvegetative cover classification.—Surface water can be measured and monitored using both single-band IR (0.8-1.1 m) and multiband analysis. Both computer-assisted and conventional photointerpretation techniques have been effective (Klemas and Polis 1977, Ritchie et al. 1976). In fact, the National Aeronautics and Space Administration (1976c) developed a set of manual procedures, computer programs, and graphic devices designed for efficient production of precisely registered and formatted maps of water from digital Landsat MSS data.

Using computer-assisted techniques, Mausel et al. (1974) were able to identify and map all surface water bodies over 0.5 ha. In addition, they were able to identify five distinct classes of water and correlate them with several measures of water quality: (1) degree of silt in water, (2) depth of water, (3) presence of macro- and micro-biotic forms in the water, and (4) presence of various chemical concentrations in the water. In a study by Boland and Blackwell (1975), Landsat MSS data and the trophic status of lakes in the northeastern United States were used to develop predictors for two trophic indicators, to estimate lake position on a multivariate trophic scale, and to automatically classify lakes according to their trophic state. Their results using computer-assisted techniques indicated a potential for satellite data in lake surveys and for monitoring water-related activities. However, further refinements in the process are needed to make it an operational tool. In another hydrologic application, land use data derived from Landsat imagery improved significantly several streamflow characteristic equations in Delaware, Maryland, and Virginia (Pluhowski 1977).

Sampling schemes using Landsat data, aircraft observations, photographic measurements, and ground measurements can be useful in water inventory. Gilmer and Work (1977) used a 0.8% random transect sample and linear regression analysis of Landsat and aircraft observations of numbers of water bodies to estimate the adjusted number of water bodies in North Dakota. The estimates were within 3-8% (May and July imagery, respectively) of estimates made from low-flying aircraft. Information on lake numbers was necessary for managing migratory waterfowl. Thematic maps and statistics relating to open water were developed by Work (1976) using multiple-band techniques. However, he recommends a combination of single- and

multiple-band techniques to cut costs in operational applications of the procedures.

A stratified-random double-sample design was used to estimate water in three Virginia counties (Aldrich and Greentree 1977). Their technique used a combination of 1:125,000 BW photographic enlargements of Landsat bands 5 and 7, 1:120,000 scale color IR photographs, and ground checks to estimate water by type, size, accessibility, and utility classes. The cost was low, and the sampling error for the three-county area was less than 10%.

Nonvegetated soils in agricultural areas of the country can be accurately delineated and quantified by soil map unit composition using Landsat data and digital analysis procedures (Kirschner et al. 1977). However, mapping soils where vegetation covers the ground is particularly troublesome when using Landsat data. This is probably why there is a greater emphasis on aerial photography for soils mapping. Using Landsat photographic data as a background for soils mapping, however, greatly enhances information that can be deduced about hydrology and land use according to Westin and Frazee (1975). They also found that color composites were adequate for locating most boundaries between soilscapes. Regardless of soils type, it is interesting to note that soil moisture mapping over large areas can be carried out using satellite data if suitable weather conditions prevailed at the time of the imagery (Palabekiroglu 1977). This could be a very difficult requirement to satisfy in practice.

Special considerations.—There are many problems associated with the use of digital Landsat MSS data and the application of these data. These problems are usually associated in some way with cost, geometric fidelity of the data, effects of topographic relief, and the pixel by pixel registration of two or more Landsat scenes to make use of more than one data set. These problems are being pursued by researchers across the country; however, none of them has been satisfactorily resolved at this date with technology transferred to the user community.

The greatest cost of using Landsat data is not in the data itself but in the computer time required to perform the various routines involved. For instance, the cost of one set of tapes for a single scene covering about 6 million acres (2.43 million ha) is only $200. However, to have the data geometrically corrected to a map will cost in the neighborhood of $800-$1,000. This is before classification routines are used.[7] To reduce costs of processing Landsat data, computer programs must be efficient and use assembler language peculiar to the particular computer as much as possible.

[7] *Conversations with Roger M. Hoffer, Laboratory for Agricultural Remote Sensing (LARS), Purdue University, West Lafayette, Ind.*

One effective way of reducing computer costs is to use table look-up rules. These rules have made processing Landsat data by computer far more efficient (Shlien and Smith 1975). Table look-up schemes are based on a high correlation of the spectral intensities in the four MSS bands. This correlation reduces the number of distinct intensity vectors in an image to the order of several thousand compared with over 16 million possible vectors. The distinct vectors are stored together with the ground cover classification in the computer core memory. The accuracy of classification is comparable to classification by conventional methods but by an order of magnitude faster.

Computer programs for converting the coordinates of Landsat pixels to Universal Transverse Mercator (UTM) or geographic coordinate systems are readily available. Unfortunately, the most powerful programs with the best geometric correction algorithms require large computers with large storage capacities. The programs are usually written in a programming language which makes them unusable for most Fortran applications. Fortunately, the Image Processing Facility (IPF) at Goddard Space Flight Center, NASA, Greenbelt, Md., and the EDC have developed all-digital Landsat data processing systems that will be operational in late fall of 1979. The Goddard system will be capable of producing about 200 scenes per day as opposed to the present rate of 15 scenes per day. The IPF data will be provided to EDC on high-density digital tapes. EDC will make digital geometric and radiometric corrections to computer-compatible tapes as well as to all hard-copy imagery. This is a large step forward and will permit many more agencies to use Landsat data that could not previously because of the data quality and the need for greater geometric accuracy. Developments in Landsat digital enhancement at EDC should also improve the interpretation of Landsat images by manual technique (Rohde et al. 1978).

Boundary lines delineated by computer-assisted techniques using feature classifiers are often indistinct because pixels of mixed spectral data are misclassified. For example, when Landsat data were used to map land cover in Pennsylvania agricultural areas, many pixels overlapped small irregular field boundaries and caused difficulties in classification (Petersen and Wilson 1974). This problem is not uncommon and, in fact, could be called universal where land cover is heterogeneous in nature.

The boundary pixel problem is much like the "salt and pepper" problem of classification maps. Here, individual pixels of data classified different from surrounding pixels, sometimes erroneously as in the case of boundary pixels, detract from the classification map. This "salt and pepper" effect can be eliminated using an algorithm that refines the

computer classification of multispectral data (Kan 1975). The algorithm eliminates sets of data smaller than a prespecified size by merging them with the surrounding area. With 5- to 10-acre (2- to 4-ha) minimum mapping standards, this process would cause no problems with mapping accuracy.

Determining the final accuracy of a map produced by either manual or computer classification is always a problem. There are a number of techniques offered to solve this (Hord and Broomer 1976; Kan 1976a, 1976b; Genderen and Lock 1977). The Hord and Broomer technique calls for a random selection of plots for ground checking (with replacement) to meet the accuracy level desired. A table is provided from which the minimum number of correct sample points required to meet the accuracy desired is read for the lower 95% confidence limit. Whether or not the classification meets this requirement is determined; if not, then the accuracy actually achieved is determined. In a somewhat similar approach, Genderen and Lock (1977) have come up with a simple but reliable method for determining the sample size acceptable for valid statistical testing of land use map accuracy. Their method takes into account (1) the probabilities of attributing one land use to another, (2) the probability that the wrong class is erroneously included in any one class, (3) the proportion of all land mistakenly interpreted by the interpreter, and (4) the determination of whether errors are random or subject to a persistent bias. This is a much more appealing approach because it takes into account all types of error.

Kan (1976a) takes a different approach that is oriented more toward computer-assisted classification maps using Landsat data. He describes a procedure that takes the form of a theorem relating accuracy of all map classes to derived two-class map accuracies. A derived two-class map accuracy refers to the classification map (M-classes) when treated one class at a time versus the remaining classes. In another approach, Kan (1976b) evaluated the per-pixel Landsat classification accuracy of a map using a sample size which is small enough (2 by 2 pixels) to reflect pixel classifications but is large enough to absorb possible errors by misregistration and mixture pixels.

If spectral signatures for land cover are to be extended from one satellite image to another or from one location to another within a single image, corrections are usually required for differences caused by solar and atmospheric effects. This is somewhat analogous to sensitometric calibrations on color film to account for differences in solar and atmospheric conditions at the time of photography. The need for a technique to calibrate changes in solar and atmospheric effects has been well defined and documented by Dana (1978). In his research, he compared Landsat MSS data with terrain reflectance data measured from a low-flying aircraft using a four channel radiometer, an irradiance meter, and a video camera with recorder to provide support photography. His results showed that when the data were not adversely affected by soil moisture changes, a high correlation existed between Landsat radiance and terrain reflectance. A linear atmospheric model was developed by regression and is undergoing further testing.

Other investigators have developed empirical techniques for calibrating Landsat and photographic data for solar and atmospheric parameters to transform spacecraft radiance measurements to absolute target reflectance signatures (Rogers and Peacock 1973). A photometric technique that utilizes reflectances from scene shadow areas for calibrating remotely sensed data has been used extensively (Piech and Walker 1972, Talerico et al. 1977). Although the photometric technique is most appealing from an operational standpoint, it is difficult to learn details of the procedure. Its application to Landsat data with 80-m resolution seems inappropriate except in areas of steep terrain.

It is generally recognized that classification of multispectral data from a single time period alone may not be enough to permit sufficiently accurate classification and mapping of information from forest and rangeland. Spectral similarities of classes within a scene and spectral variability within a class, from one location to another and from time to time, may not permit adequate results. However, ancillary geographic data (including topography) and additional MSS data from other time periods may be used to improve classification and resulting resource information (Strahler et al. 1978). Topographic variables have a significant effect on Landsat signals and feature classifiers. The aspect of sloping terrain relative to the sun's azimuth is the major cause of variability (Cicone et al. 1977). Preliminary indications are that including topographic ancillary variables, stratifying on these variables, and developing training statistics within each stratum improves the performance of the feature classifier. However, more work is needed in this area to determine the full implication of these results.

Shadows in mountainous terrain caused by low sun angle at the time of Landsat passes create problems in feature classification. In most application demonstrations of Landsat data, these pixels are either left unclassified or they are classified like surrounding pixels. To reduce the effect of topographic shadow in Landsat data, Hart and Maxwell (1978) tested three transformations of Landsat data: (1) each spectral band value was divided by the average of all bands, (2) each spectral band value squared was divided by the average of all bands,

and (3) each spectral band value was divided by the square of the average of all bands. The normalization of single band reflectance (brightness) with the average of all bands was most effective for highly correlated original bands of data and least effective for inverse relationships on the red/IR response vegetation. They found that the accuracy of classification was higher for some between class distinctions based on subtle spectral difference detection but the accuracies were lower for class distinctions based on the magnitude of brightness. Accuracies were generally degraded by loss of brightness information.

The accuracy of multidate image registration is important for analyzing temporal data to improve cover classifications as well as to detect changes in the land cover. Detecting changes in the land cover as a result of land use and management practices will require selecting image dates that are compatible (seasonally) and geometrically corrected so that any pixel can be registered within a half a pixel of its contemporary on another image. The new process for geometrically correcting Landsat data tapes at EDS (National Aeronautics and Space Administration 1978) will provide temporal registration offsets between two Landsat images with the same World Reference Frame Numbers of <0.5 pixel. However, registration accuracy will depend to a great extent on the number of ground control points used, the accuracy of the maps on which coordinates are measured, and the accuracy of the coordinate measurements. Examples of some of the problems in change detection are reported by the Pacific Northwest Land Resource Inventory Demonstration Project (1978). They reported that multidate analysis of two Landsat images were overlayed and registered in a temporal analysis to detect land cover changes over a 3-year period. They used Laboratory for Agricultural Remote Sensing, Purdue University (LARSYS) and Image 100 (General Electric) systems in their data analysis to determine the location and extent of land cover changes. Classifying land cover for each date independently and then comparing the two for changes was unsatisfactory because most changes resulted from errors in classification. When a ratio of the two scenes was calculated and analyzed, it resulted in the detection of change but the method had only limited accuracy. The entire area of change detection including conventional photo interpretation, computer interactive interpretation, and automated interpretation will be investigated during the next few years.[8]

Although spectral data alone is used in most demonstrations of Landsat data applications, some people feel that spatial data should be given more attention (Sayn-Wittgenstein and Kalensky 1975). They say the reason why spatial data is not given much attention is that spectral data can be analyzed on a per pixel basis, whereas spatial data requires several to many pixels to obtain significant spatial patterns. They feel that, whereas spectral values are well known and easier to use, the analysis of spatial data is more difficult and requires a knowledge of complex mathematical approaches to define the spatial geometry of the data. Spatial data may be a requirement for many applications to obtain required classification accuracy in the future; however, its present use is extremely limited.

[8]*U.S. Department of Agriculture, Forest Service. 1978. Detecting and measuring changes in the renewable resource base using remote sensing techniques. A tripartite research and development study plan developed by the National Forestry Applications Program, NASA/JSC, Houston, Tex.; Special Mapping Center (Engineering Division), Reston, Va.; and the Resources Evaluation Techniques Program, Rocky Mountain Forest and Range Experiment Station, Fort Collins, Colo.*

Thermal Scanner Data

The uses of thermal scanner data in classification and mapping generally fall into five categories: (1) fire detection and mapping, (2) vegetative stress detection, (3) land use and vegetative cover mapping, (4) ground water mapping and monitoring, and (5) geological structure classification. The use of thermal bands of data in MSS data analysis was covered in the section on Airborne Multispectral Scanners and will not be repeated here.

As brought out in the section on Airborne Multispectral Scanners, classification and mapping in the normal sense is rather difficult to do using thermal data alone. However, thermal data have been found useful to map thermal anomalies in the Yellowstone National Park. Producing a geothermal map uncovered a number of problems inherent in the thermal mapping process (Williams et al. 1976). Thermographs can be produced relatively free of geometric distortion if several provisions are made in the production of imagery. For instance, the line scan device must be stabilized about the three axes in the aircraft or the instrument motion around the axis must be recorded on tape with the video signal for stabilization of the imagery during film strip reproduction. In addition, the authors report that the average aircraft altitude above ground, the aircraft ground track, and the aircraft speed must be known to reproduce the data. Imagery must be rectified and the radiation response of the line-scan device must be constant.

Like geothermal anomalies, forest fires create targets of intense heat that are easily detected by thermal line scanners. An operational system utilizing two detectors sensitive in the 3- to 4-μm and 8.5- to 11.0-μm portions of the spectrum has been in use since 1971 (Hirsch et al. 1971). This system can detect targets as small as 0.09 m^2 at 600° C against backgrounds ranging from 0° to 50° C from

altitude of 5,000 m. Polaroid prints are dropped to the fire boss with up-to-date fire information. The system can mark hot spots too small to print and provides information not available on one-detector units. The system is now operational for detection patrols, fire mapping for large fires, and mapping during mop-up operations on large fires. A smaller, lightweight IR line scanner is used as a fire spotter and can detect fires as small as 0.09 m^2 in size from 600 m above the terrain (Kruckeberg 1971).

Trees under the stress from bark beetle attacks have been shown in exhaustive field experiments to have temperatures higher than surrounding healthy trees (Weber 1971, Schmid 1976). Although temperature gradients as high as 7° C have been recorded, on the average the difference between infested and control trees is within 1° C. This small difference is usually masked by macroclimatic conditions that exist at the time of a thermal scanner pass. Although previsual detection of vegetation stress based on thermal differences is theoretically possible, detectors available today are not sensitive enough to overcome the prevailing weather conditions, closed cover, and winds that mask the warming effect of an infestation.

In summary, from what we know about thermal scanners there are possibly five mapping tasks for which thermal imagery will be useful: (1) geothermal hot spots under vegetation, (2) old stream channel locations, (3) high soil moisture, (4) thermal water pollution, and (5) spot fires and fire periphery.

Microwave Data

Of all remote sensing data, microwave is the least known and the least effective for wildland resource management uses today. This is probably because active (radar) and passive microwave systems are thoroughly understood by only a few people, the resolution of radar systems is comparatively poor, and other systems such as aerial photography and MSS's are easier to understand and use, and thus are more appealing. This has effectively limited applied research using active and passive systems.

Active Microwave

Because of its all-weather capability, side-looking, airborne radar (SLAR) is attractive for mapping in areas that are under nearly continuous cloud cover. Two such operational applications have been reported during the past 10 years. One application was in a portion of the Darien Province in the Republic of Panama (Crandall 1969). A portion of the Pan American Highway could not be completed because adequate map information was lacking. Using 5-foot corner reflectors at 13 locations as control points, radar imagery was produced and mosaics made to fill the information requirements. In 1970 Project Radam was organized to map more than 4.6 million km^2 in the Brazilian Amazon (Roessel and Godoy 1974). As a result, 160 semicontrolled SLAR mosaic sheets were released for public use. Each sheet covered 1° of latitude and 1.5° of longitude. For the first time, this vast area of rich resources was mapped for exploration. Results of the Panama and Brazil mapping projects indicate that radar mosaics can be made of the terrain using a minimum number of control points with fairly reasonable positional accuracy. Unfortunately, there is no evaluation of the informational content of these radar images for wildland resource management.

Several other researchers have made evaluations of radar imagery for wildland resource classification and mapping. For example, Bajzak (1976) in a test of radar imagery for forestry purposes, found that land formations could be clearly recognized on the radar imagery. However, the small scale of the imagery and interference inherent in the equipment limited the usefulness of the systems. Working with radar images with a ground resolution of 10 m and enlargements to 1:50,000, Francis (1976) found the images useful for surveying forest resources in the humid tropics. By adjusting the images to minimize reflections from vegetation, he was able to obtain an image of the underlying terrain. Drainage patterns, swamps, and flood plains, land under cultivation, mangrove forests, swamp forests, wet forest, dry forest, and general topographic features can be detected on the SLAR imagery for tropical forest surveys (Allen 1975).

According to Moraine and Simonett (1967), radar images contain subtle differences which the unaided or untutored eye at first sight cannot distinguish. To assist the interpreter, they developed a color-combining system to enhance the subtle distinctions and thereby expand the interpreters' detection and discriminatory abilities. Outputs of a data matrixing unit were presented to the three electron guns of a CRT in a color television set where they were combined in various colors to aid interpretation. Although image enhancement techniques have become commonplace in remote sensing, radar imagery still has not been accepted for general use because of problems in using the data.

There are a number of problems that exist when using radar imagery that must be understood and overcome. Not the least of these problems are proportionality geometrically in the near range, image layover causes areas of no detail for interpretation, shadowing with no interpretation data, and differences in range and azimuth scale. In areas

where slopes exceed 35% and 1,000 m in elevation, the usefulness of radar will be marginal unless careful consideration is given to both the geometry of the imaging system and the terrain itself (MacDonald and Waite 1971). Another problem is that magnification of radar imagery during interpretation is limited by the speckled effect in radar images of homogeneous scattering areas (Moore and Thomann 1971). In other words, the image falls apart. In a 15-m resolution system the limit of useful magnification is 10X. Thus, the small scale and limited resolution of radar imagery preclude interpretation of details. Enough detail is present, however, to categorize regions, and by sampling provide more detailed regional descriptions (Nunnally 1969).

Those applications where radar imagery will have its greatest potential are water, snow, or sea ice mapping; soil moisture mapping; drainage networks (McCoy 1969); landform mapping; combined physiographic and slope category maps (Nunnally 1969); and delineations of major geomorphic regions. Radar might have a role someday in preparation of small-scale regional or reconnaissance maps of vegetation types, delimiting vegetation zones that vary with elevation, tracing burn patterns from previous forest fires, determining the timber line, and identifying species by inference in areas characterized by monospecific stands (American Society of Photogrammetry 1975). Operationally, the U.S. Coast Guard uses radar to locate sources and map oil spills for purposes of prosecution. They also use radar for real time maps of ice conditions on the Great Lakes (Fischer et al. 1976).

Passive Microwave

Passive microwave is in its infancy and any applications are primarily developmental in nature. For instance, the USGS is studying the dielectric properties of soils, geological materials, snow, ice, and other materials conducive to layering experiments and soil moisture (Fischer et al. 1976). We need to learn more about the dielectric properties of vegetation, soils, and water before passive microwave systems can be evaluated for wildland resource applications.

INTERPRETIVE INFORMATION FOR SPECIFIC APPLICATIONS

Most interpretive applications of nonphotographic data relate to vegetative conditions including phenology, geology and unstable conditions, soils, and hydrology including soil moisture and water quality. As mentioned previously, most interpretive applications are also closely related to classification and mapping.

Vegetation condition.—To detect and flag trees or groups of trees in the forest that are infested with bark beetles or disease is a long-term goal in forestry. It is also a goal for states with high-value fruit tree crops. Although there have been attempts to detect green trees under attack by bark beetles (Weber and Polcyn 1972) and diseased trees infested with root rot (Weber and Wear 1970) the results have been negative. In citrus plantations there has been some success (89%) in identifying trees affected by the young tree decline using MSS data in the 0.82- to 0.88-μm band from an aircraft at 1,500 feet (Edwards et al. 1975). The MSS data indicated reflectance differences for trees identified as healthy on the ground which may be a clue to previsual detection. However, because some limited success has been achieved before in fruit plantations and forests, there does not seem to be much reason to believe that these results are any more conclusive.

Knowing the phenological schedule of range and forest land development could be helpful in some wildland management activities, planting programs, harvesting, grazing, insect control, and to a certain extent fire control. Activities are regulated by seasonal changes in vegetation. Image densities for Landsat band 5 (red wavelengths) and band 7 (near IR wavelengths) in the ratio (band 5 - band 7)/(band 5+ band 7) correlated well with forest vegetation changes (Ashley et al. 1975). The ratio is lowest with leaf-off and steadily increases with leaf development. These seasonal differences are also important in understanding growth and yield relationships (Ashley and Rea 1975).

Geology and unstable conditions.—Geologists around the world are finding that Landsat photographic data can be useful where no other data exist. One such example is in Turkey where bands 5 and 7 images were visually interpreted to prepare geologic, tectonic, and geomorphologic maps (Kayan and Klemas 1978). Band 7 was most valuable for identifying geologic formations, fault lines, and geomorphologic slope contrast. Band 5 supplemented band 7 by providing information on rock-soil boundaries, relationships between vegetation and structure, and vegetational tonal differences between steep slopes and subsurfaces.

Because it is necessary to interrelate various types of remotely sensed data, to integrate remotely sensed data with other sources of information, and to accommodate the wide dynamic range of electronic detectors (the dynamic range of Landsat detectors is estimated to be four times that which can be accommodated on film), there has been an emphasis in

recent years on research and development of computer-assisted processing and interpretation systems (Fischer et al. 1976). In reviewing progress in remote sensing, they found that Landsat will disclose large structural features on the earth's surface only visible on the uniform synoptic view of Landsat; geologic and geohydrologic features depending on the angle of illumination of snow, water, or vegetation distributions; distributions of some rock types, geochemicaanomalies, and alteration products; and surface water availability, surging glaciers, snow lines, and sedimentation.

Some characteristic features of rotational landslides have been identified on Landsat data. These characteristics are tonal mottling, tonal banding, major and secondary scarps, and ponds (Sauchyn and Trench 1978). The authors recommend 1:250,000 enlargements for regional analysis and 9- by 9-inch (23- by 23-cm) aerial photographic transparencies for detailed identification of landslides. Band 7 was most useful to accentuate ponds and shadows. They found that examination of both bands 5 and 7 was most suitable and under ideal conditions some landslides could be recognized. However, they do not recommend Landsat for detailed regional mapping where aircraft imagery is available. Landsat may be useful, however, for preliminary landslide recognition in relatively unknown areas.

In eastern Canada, Landsat imagery provided useful information to detect landslide hazards (Gagnon 1975). For example, bands 6 and 7 give good data on high ground water tables, high water content of surface material, and some buried valleys. Radar X-band real aperture (SLAR) did not add much information beyond that obtained by Landsat. However, thermal scanner imagery gives excellent results on surface water conditions, ground water level, seepage, infiltration, and saturation, but for best results the imagery must be combined with photography. Flows from water bodies and seepage are analyzed best through the study of temperature differences.

Not all geologic efforts have been successful, however. For example, Siegal and Abrams (1976) found that computer-aided supervised and unsupervised classification schemes, using computer-aided techniques, could not correctly classify rock formations (lithologic units) found in the field. They feel that this reflects the effect of inhomogeneity of geologic units and the similarity of their spectral signatures in the Landsat bands. Only 50% accuracy was achieved in classification.

Soils.—The amount of exposed soil and the degree and type of grass or other vegetative cover, which is a function of the seasons, have a strong relationship with Landsat spectral values. Landsat soil/grass four-band spectra at the end of the dry and grass dieback season are in reality the soil spectra (Levine 1975), and the Landsat four-band spectra for serpentine and sedimentary-derived soils are enough different from each other and the background to be classified by interactive unsupervised classification techniques. However, not all soil classification is this simple and, in fact, when the natural vegetation is heavy, it can significantly mask and alter the spectral response of the ground as measured by aircraft and satellite MSS (Siegal and Goetz 1977). Low albedo materials are significantly affected and may be altered beyond recognition by only a 10% green vegetative cover. As with Levine (1975), these authors found that dead and dry vegetation does not greatly alter the shape of the spectral response curve. The ratios of bands 4/6, 4/7, 5/6, and 5/7 are decreased by increasing amounts of vegetation. Tucker and Miller (1977) used regression analysis of soil spectral reflectance in the 0.35- to 0.80-m region to quantify maxima and minima for soil-green vegetation reflectance contrasts. This technique could be important to estimate the soil spectra reflectance and to quantify the wavelengths of maximum soil-green vegetation reflectance contrast.

Passive microwave usually receives very little attention in wildland resource applications. However, in one test on the west side of the San Joaquin Valley in California, Estes et al. (1977) found highly significant linear correlation between image tone density in the photographic output and moisture content in the top 5 cm of soil.

Hydrology.—A number of hydrologists have found that land use or thematic information from Landsat data are useful in hydrologic models (Dallum et al. 1975, Jackson et al. 1975, and Blanchard 1975). However, Blanchard and Baush (1978) found that spectral calibration of runoff curve numbers cannot be achieved on watersheds where significant areas of timber are within the drainage area. They found that wet surface conditions and vegetation grown throughout the year will prevent classifying runoff potential based on visible light only.

Monitoring the quality of water has become an important application of remote sensing and will gain greater use in the future. To detect senescent or dystrophic bodies of water, the presence and levels of chlorophyll "a" appears to be an important parameter. Chlorophyll "a" has been associated with eutrophication of water bodies which limits them for recreation, water supplies, and other purposes. Furthermore, low concentrations of chlorophyll "a" may be due to toxic substances from industrial wastes or other sources. A statistically significant linear relationship has been found

between aircraft-measured MSS data in the 0.44- to 0.49-μm, and the 0.70- to 0.74-μm spectral bands and chlorophyll "a" measurements for the same area in the James River in Virginia and New York's Bight ocean area (Johnson 1978).

To monitor oil spills, UV video systems have shown a great deal of promise although these systems are limited to daytime use under good weather conditions. There is a definite relationship between radiance of oil in the UV range and the type and thickness of oil (Wezernak and Polcyn 1971). Because of its "good day only" restriction, however, UV remote sensing is not likely to satisfy emergency situations. Microwave systems with all-weather capability have the greatest potential for responding to emergency situations. The U.S. Coast Guard has found a synthetic-aperture SLAR system provides the best results for detecting both natural and manmade oil slicks (Klaus et al. 1977).

Perhaps the greatest use of thermal imagery to date has been to relate gray scale values in the imagery to water temperatures, observe the source of the temperature gradient, and interpret the effect on the aquatic environment. Similar results can be obtained using calibration plates to accurately calibrate thermal IR scanner systems for water temperatures (Hoffer and Bartolucci 1972).

The best time of day or night for thermal imagery is related to the purpose of the mission. For example, nighttime thermal imagery is superior to daytime imagery in distinguishing rock types and map faults and fracture zones (Rowan et al. 1970) if acquired just before dawn. Generally speaking, however, tone signatures and image quality degradation in information content increases as night progresses. In daylight hours, equal amounts of reflected and thermal IR are returned to earth-oriented sensors operating between 3.0 and 4.5 μm. Therefore, an IR detector operating in this region may record phenomena related to reflected as well as reradiated energy (Estes 1974). For daytime operations, thermal scanning is confined to the 4.5- to 5.5-μm and the 8.5- to 13.5-μm regions. Exceptions to this are forest fires and volcanic activities (American Society of Photogrammetry 1975). Environmental conditions including clouds, heavy overcast, surface winds, time of day, and seasonal changes are sources of error in thermal imagery that are difficult to overcome and make the imagery difficult to use except under the most ideal conditions.

MEASUREMENTS OF RESOURCE PARAMETERS

Because nonphotographic data are nonstereoscopic by nature, only one- or two-dimensional measurements can be made. Measurements that are most successful are relative closure (percent of ground covered by the projection of vegetation foliage to the ground) and area. Because MSS and thermal scanner data are collected in pixels with ground coverage determined by the IFOV of the scanner, area measurements are based on the summary of all pixels adjusted for geometric errors classified in a particular category. The number of pixels in a category divided by the total in the mapped area, multiplied by the known total area, will result in the area in each category. Estimates such as these have been discussed under Nonphotographic Classification and Mapping. Generally speaking, the accuracies are about 80% ±5% at the 90% probability level.

Tree and stand measurements.—Attempts to relate spectral values from the four Landsat bands to timber volume and/or basal area have been unsuccessful. Successful use of Landsat MSS data in timber volume estimates were made by stratifying the population by type and condition classes with Landsat data and sampling within strata using aerial photography and ground plots (Titus et al. 1975, Harding and Scott 1978, Oregon State Department of Forestry 1978). In one instance it was found that Landsat data could not be used effectively to stratify forest land (Colwell and Titus 1976). In this example, the Sam Houston National Forest in Texas was found too homogeneous to provide meaningful strata.

Radar might have a role someday in discrimination of structural subtypes in cutover, burned, and regrowth forest; deriving estimates of vegetation density in sparsely vegetated areas; and supplementing high-altitude low-resolution photography in which texture differences related to vegetation are weakly expressed (American Society of Photogrammetry 1975).

Biomass measurements.—Measurements of species composition in the forest understory based on the overstory properties are not reliable (Sadowski and Malila 1977). Site is probably a much better basis for inferring understory density and composition, according to the authors. On the other hand, they say that understory biomass production potential would be better inferred on the basis of overstory density with improvements from the addition of site information. Although inferences about understory vegetation based on crown closure measured from MSS data and ancillary site information are a possibility, there is a great deal of research that must be done beforehand.

Following the Landsat-1 satellite launch in 1972 a great deal of effort was expended in developing relationships between the multispectral data and

forage production. In one experiment, Carneggie and DeGloria (1974) examined Landsat reflectance and irradiance data and demonstrated that (1) the time when germination occurred can be determined quantitatively from analysis of Landsat irradiance data, (2) the length of the green feed period can be determined and correlated with relative amount of forage produced in a given area, (3) Landsat reveals the location and extent of ranges affected by favorable or unfavorable climatic conditions that cause above and below normal forage conditions and production, and (4) Landsat data can provide a permanent record of range conditions at a given date and for a given year. Thus, Landsat seemed assured of a spot in the range managers' tool kit. However, there seems little of record to show that managers have used Landsat.

Many investigators have tried to quantify the forage production using computer-aided techniques. Some found that the red band (band 5) energy is strongly absorbed and the near IR band (bands 6 and 7) energy is somewhat more reflected by dense green vegetation (Deering et al. 1975). From this they hypothesized that a ratio of red to near IR should be an index of the greenness of a vegetative scene. This relationship also suggested that the difference between bands 7 and 5 normalized over the sum of these values can be used as a "vegetative index" or "band ratio parameters." Although this index holds up pretty well for very high biomass values, there is a threshold value or ground cover below which the estimate of biomass is unreliable. The capability of estimating green biomass has been demonstrated at 250 kg/ha increments in the 500-1,500 kg/ha range of productivity (National Aeronautics and Space Administration 1977). According to NASA, the normalized difference ratio of bands 5 and 6 was best for statistical determination of the amount and seasonal condition of rangeland vegetation in the Great Plains.

In another, somewhat related study, spectral reflectance measurements on sample plots in shortgrass prairie indicated that green biomass, chlorophyll concentrations, and leaf water content are directly interrelated to "functioning green biomass" (Tucker et al. 1975). Correlations between reflectance and these three measures were calculated at 91 wavelength intervals between 0.350 and 0.800 μm. Increasing amounts of dead vegetation during the season had little affect on the correlations. Tucker and Maxwell (1976) developed a linear relationship between integrated reflectance values (0.350-1.000 μm) and several canopy or plot variables (total wet biomass, total dry biomass, leaf water content, dry green biomass, dry brown biomass, and total chlorophyll content). Their purpose was to determine the relative statistical significance between integrated reflectance and the canopy variables for various wavelengths and bandwidths. Three spectral regions had strong statistical significance: 0.35-0.50 μm, 0.63-0.69 μm, and 0.74-1.00 μm in both the early and late growing season. There is greater spectral sensitivity early in the growing season between reflectance and grass canopy variables. Landsat bands 5 and 7 and RBV band 2 are well suited to biological remote sensing. Although more is being learned every day about quantifying the biomass from MSS data, there is nothing available at the present time to indicate that a breakthrough is imminent.

Other measurements.—Fuel moisture measurements may some day be monitored by satellite remote sensors. For example, there are indications that 1-hour time-lag fuel moisture estimates can be made over large forested areas with good results from synchronous meteorological satellites (SMS) (Waters 1975). However, the satellite data must be augmented with some estimates of humidity made from ground stations. The distribution of cloud cover can also be monitored and mapped from satellite data to indicate surface insulation. Some of the limitations of SMS-1 satellite data for fire danger applications are (1) in cloudy situations a surface view is almost impossible and only cloud cover information is available; (2) sensor resolution is large, so that surface information for smaller areas is lost; (3) cirrus and small uniform cloud types such as cummulus are underestimated; (4) earth location of the data is difficult by automated methods at the present time; and (5) it requires processing a great deal of data.

Snow and water area can be quantified quite readily on Landsat data. The quantification of areal extent of snow covering watersheds is a useful parameter in estimating snow water content for inclusion in water runoff prediction equations. Katibah (1975) developed an operational manual of interpretation techniques allowing for fast and accurate estimates of the areal extent of snow using Landsat enlargements. Using a combination of Landsat photographic image density slicing and radiance values from Landsat band 4, Thomas et al. (1978) measured areas of snowfields. They found that using absolute radiance values from computer-compatible tape data and consideration of the effect of topography on recorded snow reflectance were important. Using computer-assisted techniques to quantify snow cover can run into problems where cloud cover prevails. This will no longer be an issue with the advent of the "thematic mapper" on Landsat D which will include the middle IR portion of the EMS. Spectral differentiation between snow and clouds can be achieved in the middle IR portion of the spectrum (Hoffer et al. 1975). Water inventory can be accomplished equally as well by either man-

ual or computer-assisted techniques (Aldrich and Greentree 1977, National Aeronautics and Space Administration 1976c).

OBSERVATIONS AND COUNTS OF OCCURRENCES

There are very few potential applications of nonphotographic remote sensing to make observations. The observation of water pollution has been discussed previously and will not be repeated. In a study in New England, Simpson (1970b) compared the capabilities of radar, thermal IR, and BW photographs to provide data on location, size, and slope of builtup areas. He concluded that only under special operating conditions relating to weather, cost, and similar factors would one select radar or thermal IR in preference to photography.

Parker and Driscoll (1972) made a study of the application of thermal IR to big game animal counts. They flew an IR detector (0.8-13.0 μm) with a 2.5 mrad IFOV over pens containing 66 deer and antelope. They found that the temperature difference between animals and their background was enough to permit detection from either 300 or 500 feet (91.5 or 152.4 m). However, at a safer flying altitude of 1,000 feet (305 m), detection was not possible. This was primarily the result of the 2.5-m ground resolution of the scanner at that altitude.

Because animals are effectively insulated, their surface temperatures are usually considerably lower than their internal temperatures (Parker 1971). Furthermore, the surface temperature of an animal at any time depends on a number of environmental factors—the air temperature, solar radiation, atmospheric water vapor pressure, and windspeed. Parker and Harlan (1972) found that missions for deer detection by airborne thermal IR scanner should be flown during periods of no direct-beam solar radiation (i.e., sunset to dawn). This would maximize the temperature difference between the deer and its background. However, further investigations in basic thermal IR methods are recommended to resolve variations (Parker and Driscoll 1972).

COSTS

This paper has reviewed many state-of-the-art, wildland applications of remote sensing technology. From the review it is apparent that not every sensor is equally effective or efficient for every job. In fact, it would be difficult to recommend a universally used remote sensing system, a standard film scale, or season of the year for every USDA Forest Service user need. Instead, each requirement for remotely sensed data should be judged by itself and with others to select sensor parameters that will provide the most effective use of remotely sensed data in resource management activities. The more uses for a particular set of data, the more cost-effective that data will be. However, the original purpose of the data should never be compromised.

DATA COLLECTION

Data collection costs include all expenses involved in delivering the remotely sensed data product to the user. Included are costs of the aircraft, crew, film, photographic laboratory, and other internal costs peculiar to the aerial contractor. Parameters that will vary and affect the costs of aerial photography are swath width, aircraft utilization (hours/year), flight efficiency (percent), flight cost (dollars per hour), data cost (dollars per image), and the number of duplicate images to be delivered (Arno 1977). Because of these variables, the cost of remote sensing data collection is very difficult to determine except on a mission by mission basis.

As a general rule, the costs of aerial photography will decrease approximately 5% each time the photographic scale is halved (Ulliman 1975). For example, decreasing the scale from 1:20,000 to 1:40,000 will decrease the number of photographs by a factor of four (e.g., the number of photographs is reduced from 56 to 14 for every 100,000 acres (40.486 ha) of coverage (table 4)). Film and processing costs will also be reduced four times. Aircraft and flight crew costs, however, will decrease only 2.3 times (Stellingwerf 1969). This is probably because unproductive cross-country flight time is the same regardless of scale. Costs internal to the company (including overhead), in one instance at least, is about 70% of the total regardless of scale (Ulliman 1975). Thus, greater percentage savings in flying and photographic costs are masked by the high internal company costs and result in only a 5% reduction in the cost of aerial photography each time the scale reciprocal is doubled.

According to Arno (1977), the total cost of USDA medium-scale photography in 1973 was $891,000 or $4 per square nautical mile ($1.17 per km²). He continues to say that, depending on scale, film type, altitude, focal length, and other factors, the cost of medium-scale USDA photography since 1964 varied from $2 to over $13 per square nautical mile ($0.58 to $3.79 per km²). For comparison, he describes a typical cost for a more or less typical high-altitude system including a Learjet, a 6-inch (152-mm) focal length lens on a 9- by 9-inch (3.54- by 3.54-cm) film, a flight efficiency of 40%, a utilization rate of 1,000 hours per year, a swath width of 12

Table 4.—Photographic scale coverage for estimating photo requirements per 100,000 acres

Photo scale	Number acres per square inch	Number acres per photo[1] (3.6 by 7.65 inches)	Number photos per 100,000 acres
1:15,840	40	1,101	91
1:20,000	64	1,763	57
1:24,000	92	2,534	39
1:30,000	143	3,938	25
1:40,000	255	7,023	14
1:60,000	574	15,808	6
1:120,000	2,296	63,232	3

[1]60% overlap; 15% sidelap.

nautical miles (22.2 km) (1:100,000 scale), and one duplicate film copy to the user at $0.27 per square nautical mile ($0.08 per km²). Of course, changes in any of the parameters will have a great influence on the cost per unit area. If internal company costs (Ulliman 1975) are added to this typical cost, the total for 1:100,000 scale photography would be nearly $1 per square nautical mile ($0.29 per km²) or one-fourth the average cost of USDA photography in 1973.

High-altitude panoramic cameras have been used in demonstrations for wide-area dead timber and forest damage assessments in recent years. Although the concept is appealing and the resolution (0.2-1.5 m) is required for some user needs, these systems should not be used where lower resolution systems (2-5 m) will perform adequately. A 24-inch (610-mm) focal length panoramic photography system has been found to exceed the data acquisition costs of a lower resolution 6-inch (152-mm) focal length system by 39% (Arno 1977). The higher costs are generally associated with larger amounts of data and higher data processing costs.

There are very few direct references to the data acquisition costs of optical-mechanical scanners or microwave systems. However, much of the aircraft flight costs involved with aerial photography for comparable swath widths should be applicable to scanners as well. Generally, scanners require a great deal of data to be generated and processed if any substantial area is to be viewed with good resolution. For example, where 3-m ground resolutions are required, substantially greater aircraft and data processing costs are encountered with scanners than by film systems (Arno 1977). This is because imaging swath widths are greatly reduced if resolutions are to be comparable to the photographic systems.

DATA PROCESSING

Data processing in the sense used here includes preparations for and the analysis of remotely sensed data to produce resource statistics and/or maps. Both conventional photointerpretation and computer-assisted techniques are included. Any comparative cost analysis of these techniques for wildland resource management purposes should ideally be done for the same area by collateral research efforts. Unfortunately, this is seldom possible or practical. The best one can expect is a cost analysis with each remote sensing application study. However, this too is sometimes difficult to provide with operationally realistic data.

Very often we are inclined to accept new technology as best and most cost effective because new data is collected of a type and frequency of coverage previously impossible. This is particularly true if the technology is new and sophisticated (Craib 1977). However, this new technology often can do only part of a given job. Because the entire job must still be done, older, more conventional techniques must be used at least in part which add to the total cost. Sometimes the most cost-effective procedure to complete a job is the older less-sophisticated conventional technique.

Conventional photointerpretation of aerial photographs has been compared with satellite data for delineating soils types and vegetation (Eastwood et al. 1977). In their comparison of production costs for a map of soils types, slopes, and erosion areas, the authors used low-altitude BW photographs. They found that photo production costs including field checks, editing and compiling the maps was $166 per km². The map accuracy was 99%. The same map made from satellite data using computer techniques was $61 per km². An accuracy of 90% was achieved from the satellite data. Vegetation maps were made using low- and medium-altitude BW, CIR, and color films. The cost comparison for 1:250,000 and 1:24,000 scale maps was $3.35 per km² and $29.63 per km², respectively. The mapping accuracy was 95%. The same vegetation map was produced using satellite data for only $0.95 per km² on a 1:250,000 scale map base. From these comparisons, it can be said that the cost advantage was about three times

for the satellite method of soils and vegetation mapping, but the map accuracy dropped 10-15%.

Stellingwerf (1969) reports that using aerial photography will show a reduction in interpretation cost of four times for each doubling of the scale reciprocal. However, this seems rather high based on experience. Although the number of pictures to interpret, and consequently the photo preparation, handling, and set up costs are reduced four times, the interpreter must cover the same ground area in classification and mapping with somewhat less image detail to interpret. Thus, total interpretation costs probably are not reduced more than 25% for each doubling of the scale reciprocal. The cost of classifying and mapping land-use and forest cover types on 1:120,000 scale CIR has been estimated to be $0.006 per acre ($0.015 per ha) (Aldrich et al. 1976).

Computer-aided classification entails a number of distinct routines or procedural steps to correct the multispectral data radiometrically and geometrically and to calibrate the data for system errors. Depending on the efficiency of computer software programs, the efficiency of the machine-operator interface, the amount of ground calibration, number of classifications, the effectiveness of the classification procedures, and the products delivered, costs can vary widely. The Oregon State Department of Forestry (1978) forest inventory for Douglas County using Landsat MSS data cost $0.0070 per acre ($0.017 per ha). This cost was compared with the $0.018 per acre ($0.045 per ha) for a recent forest survey using conventional techniques; however, the inventory products were different. Classification maps at two scales, areas, and forest volume statistics were produced by the Landsat-based inventory. A San Juan National Forest inventory using Landsat MSS data and aerial photographs resulted in a cost of $0.0156 per acre ($0.0385 per ha) but essentially only one classification map scale and area statistics were provided (Krebs and Hoffer 1976). In the Washington forest productivity study, Harding and Scott (1978) reported a cost of $0.026 per acre ($0.064 per ha) for a Landsat-based inventory of forest resources by age and basal area classes by ownership class. A comparable inventory using ground plots and photointerpretation cost $0.04 per acre ($0.10 per ha). The Forestry Applications Program (USDA Forest Service/NASA) has reported costs of $0.03 to $0.06 per acre ($0.15 per ha) for mapping forest and forest-related resources to level II categories given in USGS Professional Paper 964 (Anderson et al. 1976).

In summary, computer-aided data classification and processing costs will vary depending on the procedure used and the data products delivered. In general, these techniques will cost $0.02-$0.07 per acre ($0.05-$0.17 per ha). The accuracies of the data products are somewhat lower than those produced by conventional procedures.

FUTURE PLANS AND GOALS

Although the USDA Forest Service recently defined its remote sensing user requirements, specific goals were not identified or responsibility assigned. With the mechanical capabilities of remote sensing advancing rapidly during the past decade and prospects for greater advancements in the future, there is a need for increasing the biological capabilities of remote sensing technology. This means defining specific goals and responsibilities for future developments.

Some of the expected advancements in satellite data collection capabilities, agency goals and recommendations, and specific remote sensing research and development needs are discussed in the next sections.

ADVANCING SATELLITE TECHNOLOGY

Technological advances in satellite-acquired, remotely sensed data look promising for the next decade (Doyle 1978). As the leader in remote sensing from earth orbiting satellites, NASA has several satellite packages either scheduled or recommended for the late 1970's and early 1980's. Landsat-3, SeaSat-A, and the HCMM satellites were launched in 1978. These satellites have been referred to elsewhere in this review.

NASA has approval to launch Landsat-D in 1981. It is proposed that Landsat-D carry a four-channel MSS and a "thematic mapper" scanner. The "thematic mapper" will gather data with a seven-band MSS from an altitude of 705 km. In addition to six bands in the visible and reflected IR regions of the EMS, one thermal IR band will be included. The ground resolution of the "thematic mapper" will be 30 m. Of some concern to the user community is the 7- to 8-day delay between data collection in adjacent swaths. This may complicate future signature development and correlations between adjacent swaths. There is also some concern among Landsat users that unless a Landsat four-band MSS is included with the "thematic mapper," the continuity of Landsat type data will be lost when Landsat-2 and Landsat-3 are no longer operational. This could be a serious problem if forest and rangeland uses of Landsat data are operational by 1981.

The space shuttle, with possibly as many as five vehicles, will carry out 30-50 missions each year. This orbital vehicle can be recovered and reused

after each mission. It is anticipated that the space shuttle will be the primary space transport system for the next 2 decades. The first orbital flight test to carry an instrumented pallet will be launched in 1980. Five experiments are scheduled in air pollution, ocean bioproductivity, lightning storms, radar all-weather surface observation, and multispectral radiometry. One flight scheduled for 1981 will reach as far north as 57° north latitude with a large format camera for near vertical photography.

There are several additional satellites scheduled in the 1980's that will have less impact on renewable resource programs. However, the reader is referred to Doyle (1978) for more information regarding these and other satellites discussed in this review.

It is likely that high-altitude photography will be flown over the United States beginning in 1979 or 1980. A joint effort by 11 federal departments and independent agencies would provide funding for 1:80,000 high-definition BW and 1:60,000 CIR aerial photography. The USGS is the lead agency. BW films would be stored and referenced at the EDC. CIR would be stored and reproduced at the Agricultural Stabilization and Conservation Service (ASCS) Photographic Field Office in Salt Lake City, Utah.

AGENCY PROGRAMS

In 1967 a program of research for remote sensing was prepared for the USDA outlining the status of remote sensing, applications, potential benefits, and research to meet future needs.[9] Seven wildland applications for which remote sensing had potential benefits were identified: (1) range surveys to aid in assessing carrying capacity, (2) soil mapping, (3) watershed inventory and planning, (4) forest inventory, (5) forest insect and disease detection, (6) detection and mapping of forest fires, and (7) detection of forest fire hazard levels. An 11-point research program was presented that would lead to the realization of these benefits. Without assigned responsibilities, however, it is difficult to determine the current status of these 11 research areas without searching the literature as was done in this review.

In 1974 the National Academy of Sciences (1974) appointed a committee to review the progress of remote sensing in resource and environmental surveys and make recommendations for research and development. They identified three applications with the greatest probability of success for a satellite system from both the standpoint of technical feasibility and potential value: (1) inventory and monitoring of rangelands conditions, (2) inventory and monitoring of forests and forest conditions, and (3) habitat inventories for use in wildlife management.

The committee report is optimistic for Landsat-type data use in operational wildland resource management. However, the report states that a Landsat-type system cannot meet all forest and rangeland inventory and monitoring needs. The committee believes that Landsat data could provide the first level of data in the design of a cost-effective multistage inventory system for greatly improving present renewable resource assessments. They called for an improvement in spatial resolution of satellite data to 10 m to allow better identification of vegetative species composition. They also concluded that broad-area coverage provided by Landsat should lead to improved wildlife habitat inventory procedures particularly in mountainous regions. Here, Landsat coverage supplemented by more detailed photographic data for sample areas is expected to provide cheaper and more effective controls for regional habitat evaluations. The committee recommends changes in future satellite MSS's to include data channels in the blue and blue-green spectral regions and additional reflective IR and thermal IR channels. However, they made very few recommendations for future work in applications other than the development of yield prediction models incorporating Landsat and meteorological satellite data. They also recommended that earth resources data processing be converted to all-digital techniques and that the primary archival medium be digital storage.

NASA has identified and defined a number of objectives for the civil space program over a 25-year period (National Aeronautics and Space Administration 1976d). Two objectives are related to National Academy of Science (1974) and USDA[8] recommendations: (1) to reach a capability to inventory the timber of the nation's forests on a 5-year cycle with yearly updates based on multistage sampling techniques, and (2) to provide timely assessments of range conditions to support efficient cattle management in the West.

NASA recognizes that multistage sampling techniques and techniques for handling species mixes must be optimized and demonstrated before operational capability can be attained. Once this has been accomplished for broad-area timber inventories, the techniques will be extended to high-resolution data to achieve required accuracies for specific area (inplace) timber inventory systems.

According to NASA, assessments of range conditions will be implemented by a range condition status center by 1982. To accomplish this, NASA has set out to develop empirical vegetation models, agromet yield models for range vegetation, and

[9]A national program of research for remote sensing prepared by a task force of the U.S. Department of Agriculture and the state universities and land grant colleges, 1967.

optimization of vegetation models to use with high resolution data.

A USDA working group in 1977 defined major departmental information requirements that could be potentially supported by application of aerospace technology.[10] These information requirements are (1) early warning of changes affecting production and quality of renewable resources, (2) commodity production forecast, (3) land use classification and measurement, (4) renewable resource inventory and assessment, (5) land productivity estimates, (6) conservation practices assessment, and (7) pollution detection and impact evaluation.

The first four information requirements have the greatest priority in project planning in the future. All seven requirements are now included in the "Secretary's Initiative" for remote sensing.[11]

CONTINUING RESEARCH AND DEVELOPMENT GOALS

By integrating the limitations of remote sensing as pointed out in this review with recommendations and goals of the National Academy of Sciences (1974), USDA's Remote Sensing Task Force,[9] NASA's 25-year plan (National Aeronautics and Space Administration 1976d), and USDA's information requirements[10] several areas of continuing research can be identified:

Early warning of changes affecting production and quality of renewable resources.—There should be a continued effort to determine whether trees attacked by bark beetles or disease can be detected previsually by airborne MSS, thermal, and microwave sensors based on their changing reflective characteristics, temperature, or dielectric properties.

Developments for registering digital data for two or more Landsat scenes to point out changes in the forest area base, changes in the forest environment caused by man or natural phenomena, and changes in range productivity should be continued. Additional research is needed to learn how to improve the selection of temporal data for change detection and how to integrate change information into a data base management system.

For national, regional, and state renewable resource inventories, there is a need to develop methods that overlay digital Landsat data with precise permanent sample locations. This would have applications in all resource assessments to update inventories for change.

Manual and computer-aided manual methods of change detection should be developed for use with Landsat photographic data products and image enhancement devices.

Land-use classification and measurement.—Determine ground cover classes (vegetation, soil, water, and other) and other conditions inherently separable within remote sensing spectral data (digital) to aid in land-use classification. Emphasis should be on separating wildland categories from developed land—agriculture, urban, etc.

Improve classification algorithms to account for within class variation, atmospheric and solar interference, topographic relief, and shadows.

Continue efforts to use digitized small-scale and very small-scale aerial photographs for land-use mapping with emphasis on separating wildlands from developed lands. Both spectral values (density) and spatial distributions should be investigated for wildland vegetation cover and condition classification.

Develop accurate methods for overlaying digital (Landsat or photographic) data with political or administrative boundaries for mapping and statistical data summaries.

Develop improved methods to determine optimum exposure of aerial films and film density calibration techniques. Exposure differences within and between photographs caused by differences in illumination, atmospheric and solar interference, and camera characteristics must be corrected to use digitized photographic data.

Continue efforts to develop spectral signature extension capabilities to use in land classification by computer-assisted techniques. These efforts should include development of improved methods for incorporating digital terrain data.

Renewable resource inventory and assessment.—There should be a continuing effort to integrate developments outlined under information requirements above in operational resource inventory.

Development of yield prediction models for range vegetation using both low- and high-resolution data should have a high priority. However, since NASA is pursuing this development, the USDA Forest Service should monitor developments closely and transfer technology when available.

Renewable natural resource inventories will rely on conventional medium- and small-scale aerial photographs for many years. Therefore, research to integrate Landsat digital data and conventional photography in multistage or multiphase sampling

[10]Memorandum with enclosures from H. L. Strickland, USDA Remote Sensing Coordinator, to USDA remote sensing contacts dated November 18, 1977.

[11]U.S. Department of Agriculture. Secretary's Initiative, Joint Program of Research and Development of Uses of Aerospace Technology for Agriculture Programs, March 8, 1978.

designs should continue. Resource parameters measured at ground and several levels of aerial photography should be investigated to develop correlations with Landsat spectral values.

Special purpose photographic acquisition systems developed by Department of Defense, NASA, and other government agencies should be investigated for their natural resource capabilities. One example is the KA-80-A optical bar camera which with its wide-area coverage and high-resolution capabilities was found useful for statewide forest insect impact assessment. The cost and overall effectiveness of this system should be weighed against the cost and effectiveness of conventional large-format cameras.

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APPENDIX A

Glossary of Terms

ADP: Automatic data processing.

Algorithm: In computing, a statement of the steps to be followed in the solution of a problem. In remote sensing, usually refers to a procedure, mathematical or otherwise, for correcting and/or classifying digital data.

Aperture: The opening in a camera lens diaphragm (field of view) through which light passes. In thermal and multispectral scanners, the entrance slit through which reflected energy is transmitted to the detectors.

Array: An ordered set of something (e.g., Landsat multispectral scanner detectors are arranged in side-by-side arrays of six detectors for each of the four multispectral bands).

ASCS: Agricultural Stabilization and Conservation Service, U.S. Department of Agriculture.

Atmospheric interference: A reduction and/or distortion of reflectance measurements made from above or from within the atmosphere, caused by moisture and particles of matter in the atmosphere.

Atmospheric luminance: The intensity and quality of light reflected from the atmosphere.

Atmospheric transmittance: The quality of the atmosphere that allows light (solar) energy to be transmitted to the Earth's surface.

Backscatter: The scattering of radiant energy into the hemisphere of space bounded by a plane normal to the direction of the incident radiation and lying on the same side as the incident ray. In radar usage, backscatter refers to the radiation reflected back toward the source.[1]

Band: A group of adjacent wavelengths of the electromagnetic spectrum sensed by a multispectral scanner or passed by a band-pass filter and recorded on photographic film.

Band-pass filter: An optical filter that allows only defined portions of the electromagnetic spectrum to pass to the sensor surface.

Bicolor film: Photographic film with two color sensitive layers.

Biomass: The total quantity of living organisms of one or more species per unit of space, or of all the species in a biotic community.[2]

[1]*American Society of Photogrammetry. 1975. Manual of remote sensing. Robert G. Reeves, ed. American Society of Photogrammetry, Falls Church, Va. p. 2,061-2,110.*

[2]*Hanson, H. C. 1962. Dictionary of ecology. Philosophical Library New York, N.Y., 382 p.*

BW: Black and white. Used as an acronym for panchromatic films and black and white printing materials.

CIR: Color infrared. A false color film sensitive to reflected infrared radiation but not sensitive to thermal infrared radiation.

Contrast: Ratio of the energy reflected from two objects. Sufficient contrast permits distinguishing between those two objects on remotely sensed data.

Crown closure: Percent of ground area covered when the periphery of all tree and/or plant crowns are projected vertically to the ground. Sometimes called canopy cover.

CRT: Cathode ray tube.

Data set: A defined set of data (e.g., digital multispectral data for a defined area).

Detector: A device providing an electrical output that is a useful measure of incident radiation.

Dielectric properties: The properties of a material or object that allow it to conduct an electrical current.

Discriminant: A mathematical expression providing a criterion for the behavior of another usually more complicated expression, relation, or set of relations.

DMA: Defense Mapping Agency, U.S. Department of Defense.

EDC: The EROS Data Center, Sioux Falls, S. Dak.

EMS: Electromagnetic spectrum. An ordered array of known electromagnetic radiation including cosmic rays, gamma rays, x-rays, ultraviolet, visible light, infrared radiation, and microwaves.

EREP: Earth Resources Experimental Package (Skylab), National Aeronautics and Space Administration.

EROS: Earth Resources Observation Systems, Geological Survey, U.S. Department of Interior.

Focal length: The distance measured along the optical axis of a lens from the optical center (rear nodal point) to the plane of critical focus of a very distant object.[1]

Geomorphic: Of or pertaining to land forms and surface features of the earth.

Ground resolution: The size of the smallest detectable or measurable detail on remotely sensed imagery.

HCMM: Heat Capacity Mapping Mission.

IFOV: Instantaneous field of view. The field of view (aperture) designed into scanning radiometer systems (thermal scanners and multispectral scanners) so that while the radiometer is scanning an arc of about 120°, only the small area in the field of view is recorded in any instant.

Illuminance: Illumination or the lighting up of a scene. In physics, the luminous flux per unit area on an intercepting surface at any given point.

Imaging sensors: Sensors which give a visual representation of electromagnetic energy from all objects within their field of view. Included are cameras and film, multispectral scanners, thermal scanners, radar and passive microwave, and video systems.

IPF: Image Processing Facility, Goddard Space Flight Center, National Aeronautics and Space Administration, Greenbelt, Md.

IR: Infrared. Sometimes used as an acronym for black and white films that are sensitive to reflected infrared radiation.

Irradiance: The amount of light received from a distant source and measured on a surface. In physics, the radiant flux density on a given surface. Usually expressed in watts per square meter.

JSC: Lyndon B. Johnson Space Center, National Aeronautics and Space Administration, Houston, Tex.

LACIE: Large Area Crop Inventory and Evaluation. A joint project of United States Department of Agriculture, National Aeronautics and Space Administration, and National Oceanic and Atmospheric Administration.

Landsat: Originally known as the Earth Resources Technology Satellite. A research and development tool to demonstrate that remote sensing from space is a feasible and practical approach to efficient management of Earth's resources. Landsat satellites contain two sensor systems: a return beam vidicon subsystem and a four-band multispectral scanner subsystem. Landsat-3 has a five-beam multispectral scanner that includes one thermal infrared band.

Landsat-1: Originally ERTS-1, was launched in June 1972 and ceased to function in January 1978.

Landsat-2: Launched in January 1975 and is still functioning.

Landsat-3: Launched in January 1978 and is still functioning. The thermal band failed in July 1978.

Landsat MSS: A four band optical-mechanical multispectral scanner. Band 4 = 0.5-0.6 μm (green), band 5 = 0.6-0.7 μm (red), band 6 = 0.7-0.8 μm (IR), and band 7 = 0.8-1.1 μm (IR).

LARS: Laboratory for Agricultural Remote Sensing.

Microdensitometry: The measurement of film density using transmitted light from a calibrated light source in units as small as 1 μm. Film densities are recorded on magnetic tape or paper charts for computer or visual analysis.

Microwave: Very short electromagnetic energy between 1 mm and 1 m in wavelength. Bounded on one side by the far infrared and on the other by very high frequency radio waves.

mrad: Milliradian. The angle at the center of a circle subtended by an arc equal in length to one-thousandth the radius.

MSS: Multispectral scanner (see optical-mechanical scanner and Landsat multispectral scanner).

Multiband: Simultaneously observed targets on several filtered bands. Usually applied to photography where two or more cameras are used to photograph targets on infrared or panchromatic film using band pass filters.

NASA: National Aeronautics and Space Administration.

NFAP: National Forestry Application Program, Forest Service, U.S. Department of Agriculture, and the National Aeronautics and Space Administration, Lyndon B. Johnson Space Center, Houston, Tex.

NOAA: National Oceanic and Atmospheric Administration.

Nonimaging sensors: Sensors which give quantitative measures of the integrated intensity of electromagnetic energy from all objects within their field of view. Included are radiometers and spectrometers.

Optical-mechanical scanner: An airborne-or satellite-borne system incorporating both an optical and a mechanical system to scan the Earth's surface. Variations in scenic brightness are translated into electrical signals which can be amplified to produce a graphic image in one or more bands of the elctromagnetic spectrum. Both thermal and multispectral scanners fall in this category.

PDS: Photometric Data Systems.

Photographic set: A set of aerial photographs covering a defined area.

Photometric: Of or pertaining to measurement of the intensity of light.

Photon: The elementary quantity or quantum of radiant energy.

Pixels: Single picture elements of digital image data recorded on magnetic tape using a microdensitometer, thermal scanner, or multispectral scanner.

Platform: The vehicle or station from which remote sensing is carried out. These include towers, low altitude aircraft, high altitude aircraft, and satellites.

Polarization: The direction of the electric vector in an electromagnetic wave (light or radio).[1]

Previsual: Detectable before it is visible to the human eye or by remote sensing in the visible portion of the electromagnetic spectrum. Plants under water stress are to some degree characterized by a breakdown in leaf structure which may affect reflectance in the infrared portion of the electromagnetic spectrum.

Radiance: The brightness of an object as seen from a remote observation point (reflectance). In physics, it is a measure of the power radiating from a unit area of a source through a unit solid angle. Typical units of radiance are watts per square meter ≥ steradian.

Radiation: The emission and propagation of energy through space or through a material medium in the form of waves.

RBV: Return-beam vidicon. A modified vidicon television camera tube in which the output signal is derived from the depleted electron beam reflected from the tube target.[1]

Resolution element: In Landsat data, one pixel or 57 by 79 m on the ground.

Resolve: To separate one image object (bar target) from another for either detection or measurement purposes.

Resolving power: The changes in resolution in an image that depend on film, relative lens aperture, lens aberations, and the angular distance of the object from the optical axis of the system.

Scale: The ratio of a distance on a photograph or map to its corresponding distance on the ground. Usually expressed as a representative fraction.

Secondary scarp: An escarpment, cliff, or steep slope formed of eroded or disintegrated rock of some extent along the margin of a plateau, mesa, terrace, or bench.[3]

Shadowing: Obstructing of a radar beam by an object elevated above its surroundings preventing illumination of the area behind it.

Signal polarization: (see polarization).

[3]*Adapted from Glossary of Geology and Related Sciences. J. J. Howell, Coordinating Chairman. American Geological Institute, 2101 Constitution Avenue, NW., Washington, D.C.*

Signature: Any characteristic or series of characteristics by which an object or ground cover is recognized. Usually used in the sense of spectral signature, as in Landsat multispectral scanner data or photographic data.

SLAR: Side-looking airborne radar.

SMS: Synchronous meteorological satellites.

Solar altitude: The altitude of the sun in degrees above the horizon. Varies with time of day, time of year, and geographic position on the earth.

Solar angle: The angle made by the intersection of the sun's azimuth and a line through true north. The angle will vary with time of day, time of year, and geographic position on the earth's surface.

Space shuttle: A reusable earth orbiting space workshop which may be launched in 1981.

Spectral distribution: The portion of the electromagnetic spectrum represented in a pictorial scene and displayed in remotely sensed data.

Spectral resolution: The finest separation that can be made between image details based on spectral data alone.

Spectral sensitivity: The wavelength or frequency of a portion of the electromagnetic spectrum which a given sensor is designed to measure.

Spectrometer: A device to measure the spectral distribution of electromagnetic radiation.

Tricolor film: Photographic film with three color-sensitive layers.

USDA: U.S. Department of Agriculture.

USGS: U.S. Geological Survey..

UTM: The Universal Transverse Mercator map projection system.

UV: Ultraviolet. Radiation which is 0.28-0.40 μm in the electromagnetic spectrum.

Vector: A quantity that has magnitude, direction, and sense. A vector is commonly represented by a directed line segment, with length representing magnitude and orientation in space representing direction. The length and orientation of the line segment has a conveyed meaning or sense.

Wavelength: In general, the mean distance between maximums (or minimums) of a roughly periodic pattern. Wavelength equals velocity per frequency.[1]

WRS: Worldwide Reference System.

Appendix B

Table B1.—USDA Forest Service remote sensing user's requirements, desired ground resolution and preferred film type, and recommendations for photographic remote sensing based on the state-of-the-art

Data user's requirements [1]			Current recommendations			
Data requirement	Ground resolution	Preferred film type	Smallest scale[2] Detection	Smallest scale[2] Measurement	Film type[4]	Platform[4]
	—m—		*---Code Numbers[3]---*			
I. Classification and mapping						
A. Vegetated cover						
1. Forest						
a. Trees (species)	0.1	CIR	4	2	Color	LAA
1) Seedlings	.1	CIR	4	2	Color	LAA
2) Saplings	.3	CIR	7	5	CIR	LAA
			9	6	Color	MAA,LAA
3) Poles and sawtimber	1.0	CIR	13	10	CIR	HAA
			17	13	Color	HAA
4) Mature	1.0	CIR	13	10	CIR	HAA
			17	13	Color	HAA
b. Stands	30.0	CIR	32	29	Color	SAT
2. Nonforest						
a. Shrubs (species)	.3	CIR	7	5	CIR	LAA
b. Stands	3.0	CIR	21	15	CIR	HAA
c. Forbs	.3	CIR	7	5	CIR	LAA
d. Stands	3.0	CIR	21	15	CIR	HAA
e. Grasses	.1	CIR	3	1	CIR	LAA
f. Stands	3.0	CIR	21	15	CIR	HAA
g. Aquatic	3.0	CIR	21	15	CIR	HAA
3. Forest wetlands	3.0	CIR	21	15	CIR	SAT
4. Floodplain vegetation	10.0	CIR	27	23	CIR	SAT
5. Estuary vegetation	.3	CIR	7	5	CIR	LAA
6. Impenetrable forest	.3	CIR	7	5	CIR	LAA
7. Fuel Type	5.0	CIR	24	19	CIR	HAA,SAT
a. Spacing						
b. Arrangement						
c. Kind						
d. Size						
e. Class						
f. Resistance						
g. Hazard type						
h. Fuel moisture						
B. Nonvegetated cover						
1. Rock (boulders, cobblestones, outcrops)						
a. Outcrop	3.0	CIR,Color	21	15	CIR	HAA
b. Cliffs-barriers	3.0	BW	21	15	CIR	HAA
2. Barren land						
a. Dunes and blowouts	3.0	CIR	21	15	CIR	HAA
b. Bare soil	.3	CIR	7	5	CIR	LAA
c. Extensive bare soil	10.0	CIR,Color	27	23	CIR	SAT
d. Element of bare soil in ground cover	.3	CIR	7	5	CIR	LAA

[1]*Summarized from the USDA Forest Service Data User's Requirements Catalog, 1973-1976. However, some requirements have been modified to conform with current general knowledge.*

[2]*Smallest scale on which required information can be detected and measured on the recommended file.*

[3]*Codes to photographic scale, required magnification, and recommended instrument or methods of interpretation are given in table 2.*

[4]*Platform and film type (Eastman Kodak)*
LAA —Low-altitude aircraft (150-3,660 m); Color 2445; CIR 2443; IR 2424; BW 3410
MAA —Medium-altitude aircraft (3,660-9,150 m); CIR 2443; IR 2424; BW 3410
HAA —High-altitude aircraft (9,150-19,820 m); CIR SO-127; Color SO-242; IR 2424; BW 3414
SAT —Satellite (over 190 km); CIR SO-127; Color SO-242; IR 2424; BW 3414

Table B1.—Continued

Data user's requirements [1]			Current recommendations			
Data requirement	Ground resolution	Preferred film type	Smallest scale[2] Detection	Smallest scale[2] Measurement	Film type[4]	Platform[4]
	–m–		---Code Numbers[3]---			
e. Dry soil	1.0	CIR	11	9	CIR	MAA,HAA
f. Wet soil	1.0	Color	11	9	CIR	MAA,HAA
3. Water						
a. Eroded streams	3.0	BW	21	15	CIR	HAA
b. Bulldozed channels	3.0	IR,Color	21	15	CIR	HAA
c. Natural blockage	3.0	CIR	21	15	CIR	HAA
d. Locate estuaries	10.0	BW,IR,CIR	27	23	CIR	SAT
e. Water locate	3.0	BW	21	15	CIR	HAA
f. Surface level and running	3.0	IR	21	15	CIR	HAA
g. Hydrologic type	3.0	BW,IR,CIR	21	15	CIR	HAA
h. 1st and 2nd order streams	1.5	CIR	13	10	CIR	MAA,HAA
i. Water courses	3.0	Color,CIR	21	15	CIR	HAA
j. Delineate	3.0	BW,IR	21	15	CIR	HAA
C. Land use						
1. Condition prior to mining	3.0	BW	21	15	CIR	HAA
		IR,Color,CIR	25	20	Color	HAA,SAT
D. Landforms						
1. Landscapes	.3	BW,IR Color,CIR	9	6	BW	MAA,LAA
2. Physiography	.3	BW,IR Color,CIR	9	6	BW	MAA,LAA
3. Landscape texture	3.0	Color,CIR	21	15	CIR	HAA
4. Landscape color	3.0	Color,CIR	21	15	CIR	HAA
5. Landscape lines	3.0	Color,CIR	21	15	CIR	HAA
6. Landscape geomorphology	3.0	Color,CIR	21	15	CIR	HAA
7. Topography						
a. Elevations	.3	BW,IR, Color,CIR	9	6	BW	MAA,LAA
b. Maps	.3	BW,IR, Color,CIR	9	6	BW	MAA,LAA
c. Slopes	.3	BW,IR, Color,CIR	9	6	BW	MAA,LAA
d. Aspect	.3	BW,IR, Color,CIR	9	6	BW	MAA,LAA
e. Range suitability	.3	BW,IR, Color,CIR	9	6	BW	MAA,LAA
f. Terrain change	.3	BW,IR, Color,CIR	9	6	BW	MAA,LAA
g. Slope length	.3	BW,IR, Color,CIR	9	6	BW	MAA,LAA
h. Channel gradient	.3	BW,IR, Color,CIR	9	6	BW	MAA,LAA
i. Slope for range suitability	.1	BW	4	2	BW	LAA
8. Drainage	3.0	BW,IR	21	15	CIR	HAA
9. Watershed	3.0	Color,CIR	21	15	CIR	HAA
E. Disturbance						
1. Erosion	.5	BW,IR, Color,CIR	9	6	CIR	MAA,LAA
2. Severe erosion	1.0	BW,Color,CIR	11	9	CIR	MAA,HAA
3. Fire						
a. Structures threatened	3.0	BW,IR	21	15	CIR	HAA
b. Area burned	3.0	CIR	21	15	CIR	HAA
4. Insect Kill						
a. Blow down	5.0	IR	24	19	CIR	HAA,SAT
b. Down timber	2.0	BW	17	13	CIR	HAA
5. Fallen dead grass and forbs	.3	CIR	7	5	CIR	LAA
6. Ground cover litter	1.0	CIR	11	9	CIR	MAA,HAA
	.3	CIR	7	5		LAA
7. Snags, den trees	.3	CIR	7	5	CIR	LAA
8. Tree cause of death	.3	CIR	7	5	CIR	LAA
9. Mortality by species	.3	CIR	7	5	CIR	LAA

Table B1.—Continued

Data user's requirements [1]			Current recommendations			
Data requirement	Ground resolution	Preferred film type	Smallest scale[2] Detection	Smallest scale[2] Measurement	Film type[4]	Platform[4]
	–m–		---Code Numbers[3]---			
10. Mortality by types	.3	—[5]	9	6	Color	MAA,LAA
11. Logged areas	10.0	Color	27	23	CIR	SAT
12. Logging residue	4.0	CIR	23	17	CIR	HAA,SAT
	.3	CIR	7	5	CIR	LAA
13. Disasters	3.0	—[5]	21	15	CIR	HAA
14. Mining	3.0	Color	21	15	CIR	HAA
a. Waste disposal	3.0	Color	21	15	CIR	HAA
b. Surface borrow pit	3.0	CIR				
15. Stand history	.3	CIR	9	6	Color	MAA,LAA
16. Trampled vegetation	2.0	CIR	17	13	CIR	HAA
17. Disturbed area	3.0	CIR	21	15	CIR	HAA
18. Urban development	3.0	CIR	21	15	CIR	HAA
19. Type of disturbance	3.0	CIR	21	15	CIR	HAA
20. Drainage facility failure	.3	CIR	7	5	CIR	LAA
21. Water resource						
a. Floating debris	3.0	BW,CIR	21	15	CIR	HAA
b. Sediment movement	3.0	Color	21	15	CIR	HAA
c. Plankton, algae	3.0	CIR	21	15	CIR	HAA
22. Disaster						
a. Fire, flood and earthquake	.5	BW,IR Color,CIR	9	6	CIR	MAA,LAA
II. Interpretive Information for Specific Applications						
A. Land use (major)						
1. Urban areas	3.0	CIR	21	15	CIR	HAA
2. Recreational	3.0	BW,Color,CIR	25	20	Color	HAA,SAT
3. Pavement ground cover	1.0	CIR	11	9	CIR	HAA,MAA
B. Wildlife habitat						
1. Forest edge	30.0	—[5]	32	29	CIR	SAT
2. Forest-agric. edge	30.0	—[5]	32	29	CIR	SAT
3. Forest-aband. edge	10.0	—[5]	27	15	CIR	SAT
4. Forest-stream edge	3.0	—[5]	21	15	CIR	HAA
5. Forest-ocean edge	30.0	—[5]	32	29	CIR	SAT
6. Forest-water edge	10.0	—[5]	27	23	CIR	SAT
C. Land use (vegetation)	1.5	CIR	13	10	CIR	MAA,HAA
D. Fire utilization corridors	3.0	BW	21	15	CIR	HAA
E. Fuel type	5.0	CIR	24	19	CIR	HAA,SAT
F. Grazeable woodland	.3	CIR	9	6	Color	MAA,LAA
G. Vegetative condition						
1. Insect effect	.3	CIR	7	5	CIR	LAA
2. Disease effect	2.0	BW	17	13	CIR	HAA
3. Disease	80.0	BW,	36	33	CIR	SAT
		IR,Color,CIR	36	33	MB[6]	SAT
4. Wildlife	.3	CIR	9	6	Color	MAA,LAA
5. Pollution effect	.3	Color	7	5	CIR	LAA
			9	6		
H. Unstable conditions						
1. Unstable areas	.5	BW	9	6	CIR	MAA,LAA
		IR,Color,CIR	10	8	BW	HAA,LAA
I. Rock slide barriers	.5	BW	9	6	CIR	MAA,LAA
		IR,Color,CIR	10	8	BW	HAA,MAA
J. Avalanche path	.5	BW Color,CIR	9	6	CIR	MAA,LAA
K. Geology						
1. Geologic structure	3.0	Color,CIR	21	15	CIR	HAA
2. Identify rock	3.0	Color,CIR	21	15	CIR	HAA
3. Describe rock structure	3.0	Color,CIR	21	15	CIR	HAA
4. Fault lines	3.0	Color	21	15	CIR	HAA

[5]*Ground resolution was estimated. No preferred film type was given in the User's Requirements Catalog.*

[6]*Multiband photographs BW 3414 and IR 2424 films with appropriate filters.*

Table B1.—Continued

Data user's requirements [1]			Current recommendations			
Data requirement	Ground resolution	Preferred film type	Smallest scale[2] Detection	Smallest scale[2] Measurement	Film type[4]	Platform[4]
	–m–		---Code Numbers[3]---			
L. Soil						
1. Low intensity units	0.5	BW,IR Color,CIR	10	8	BW	HAA,MAA
2. Soil classes and associations	.5	BW	10	8	Color	HAA,MAA
		IR,Color,CIR	9	6	IR	MAA,LAA
M. Minerals and construction materials						
1. Gravel	3.0	Color,CIR	21	15	CIR	HAA
2. Location and extent	3.0	Color	25	20	Color	HAA,SAT
		CIR	21	15	CIR	HAA
N. Phenology						
1. Leafing	.3	CIR	7	5	CIR	LAA
2. Defoliation	.3	CIR	7	5	CIR	LAA
3. Phenological stage	.3	CIR	7	5	CIR	LAA
O. Tree point occupied	.3	CIR	9	6	BW	MAA,LAA
P. Senescent or dystrophic lakes	2.0	Color,CIR	17	13	CIR	HAA
Q. Hydrological condition	10.0	BW,IR,CIR	27	23	CIR	SAT
R. Natural open areas	3.0	BW,IR, Color,CIR	21	15	CIR	HAA
III. Measurements of Resource Parameters						
A. Tree and stand						
1. Tree						
a. Height	.3	CIR	9	6	BW,Color	MAA,LAA
b. Basal area	.3	CIR	9	6	BW,Color	MAA,LAA
c. Diameter	.3	CIR	9	6	BW,Color	MAA,LAA
d. Crown length	.3	CIR	9	6	BW,Color	MAA,LAA
e. Crown diameter	.3	CIR	9	6	BW,Color	MAA,LAA
f. Sawlog length	.3	CIR	9	6	BW,Color	MAA,LAA
g. Age	.3	CIR	9	6	BW,Color	MAA,LAA
h. Crown class	.3	CIR	9	6	BW,Color	MAA,LAA
i. Bole length	.3	CIR	9	6	BW,Color	MAA,LAA
j. Annual growth	.3	CIR	9	6	BW,Color	MAA,LAA
k. Crown ratio	.3	CIR	9	6	BW,Color	MAA,LAA
l. Tree age class	1.0	CIR	11	9	CIR	HAA,MAA
2. Stand						
a. Height class	.3	CIR	9	6	BW,Color	MAA,LAA
b. Mean diameter	.3	CIR	9	6	BW,Color	MAA,LAA
c. Crown cover by species group	.3	CIR	9	6	BW,Color	MAA,LAA
d. Tree count by stand	.3	CIR	9	6	BW,Color	MAA,LAA
e. Crown cover (generalized)	3.0	BW,IR	25	20	BW	HAA,SAT
f. Tree Count	.3	CIR	9	6	BW,Color	HAA,SAT
g. Site	5.0	CIR	24	19	CIR	HAA,SAT
h. Volume	5.0	CIR	24	19	CIR	HAA,SAT
i. Accumulated growth	.3	CIR	7	5	CIR	LAA
3. Forest						
a. Percent forest with vegetation	.3	CIR	7	5	CIR	LAA
B. Grasses						
1. Age	3.0	BW,IR	21	15	CIR	HAA
2. Form class	3.0	Color,CIR	21	15	CIR	HAA
C. Forbs						
1. Form class	3.0	BW,IR, Color,CIR	21	15	CIR	HAA
D. Brush and shrubs	.3	CIR	9	6	Color	MAA,LAA
1. Diameter						
2. Basal area						
3. Height						
4. Form class						
E. Water						
1. Stream width	.3	BW	7	5	CIR	LAA
		IR	7	5	IR	LAA
2. Stream length	3.0	BW	21	15	CIR	HAA
		IR	17	13	IR	HAA

Table B1.—Continued

Data user's requirements [1]			Current recommendations			
Data requirement	Ground resolution	Preferred film type	Smallest scale[2] Detection	Smallest scale[2] Measurement	Film type[4]	Platform[4]
	−m−		---Code Numbers[3]---			
3. Size and shape	10.0	BW	27	23	CIR	HAA,SAT
		IR,Color,CIR			IR	HAA,SAT
4. Acre feet	3.0	BW,IR	25	20	BW	HAA,SAT
5. Depth	.1	Color,CIR	4	2	Color	LAA
6. Dissolved matter	3.0	CIR	21	15	CIR	HAA
7. Algae and plankton	3.0	Color,CIR	21	15	CIR	HAA
F. Snow						
1. Area	10.0	—[5]	27	23	CIR	SAT
G. Rock slides						
1. Confirmation	.5	BW,IR, Color,CIR	9	6	CIR	MAA,LAA
2. Suspected	10.0	BW,IR, Color,CIR	27	23	CIR	HAA,SAT
H. Gully erosion						
1. Length, width, depth	.2	BW,IR, Color,CIR	6	4	CIR	LAA
I. Sheet erosion						
1. Area	.5	BW,IR, Color,CIR	9	6	CIR	MAA,LAA
J. Biomass	.3	CIR	7	5	CIR	LAA
1. Annual production						
2. Standing crop						
3. Usable growth						
4. Plant density						
5. Accumulated growth (horizontal)						
6. Vegetation distribution						
7. Annual growth for area						
8. Flora by species, number and size						
9. Vegetated area						
K. Land use						
1. Area of pavement	1.0	CIR	11	9	CIR	HAA,MAA
2. Area	3.0	CIR	21	15	CIR	HAA
L. Disturbed area	3.0	CIR	21	15	CIR	HAA
M. Area of mortality	.3	CIR	9	6	Color	MAA,LAA
N. Animal counts	.3	BW,IR, Color,CIR	9	6	BW	MAA,LAA
1. Cattle						
2. Sheep						
3. Horses						
4. Burros						
O. Fuel						
1. Volume	5.0	CIR	24	19	CIR	HAA
P. Fire area burned	10.0	BW,IR, Color,CIR	27	23	CIR	SAT
Q. Dimension of structures (improvements)	.3	CIR	9	6	BW	MAA,LAA
IV. Observations and Counts of Occurrences						
A. Buildings and structures	.3	BW	7	5	CIR	LAA
1. Fences	.3	IR	7	5	CIR	LAA
2. Bridges and culverts	.3	Color,CIR	7	5	CIR	LAA
3. Works of men	.3	BW,IR, Color,CIR	7	5	CIR	LAA
4. Structural range improvements	.3	CIR	7	5	CIR	LAA
B. Water structures						
1. Canals and ditches	5.0	BW,IR,CIR	24	19	CIR	HAA,SAT
C. Transportation						
1. Woods roads	1.0	BW,Color,CIR	11	9	CIR	HAA,MAA
2. Abandoned roads	.5	BW,Color	9	6	CIR	MAA,LAA
and trails	3.0	BW,Color,CIR	21	15	CIR	HAA
3. Road location	3.0	BW,IR, Color,CIR	21	21	CIR	HAA

Table B1.—Continued

Data user's requirements [1]			Current recommendations			
Data requirement	Ground resolution	Preferred film type	Smallest scale[2] Detection	Smallest scale[2] Measurement	Film type[4]	Platform[4]
	—m—		*---Code*	*Numbers[3]---*		
D. Recreation						
1. Marine craft	1.5	BW,IR, Color,CIR	13	10	CIR	HAA
2. Archaeological sites	5.0	BW,Color	24	19	CIR	HAA,SAT
	15.0	CIR	29	26	CIR	SAT
3. Count people in or with boats	.1	BW	3	1	CIR	LAA
4. Count people in or with recreation vehicles	1.0	BW,IR, Color,CIR	13	10	Color	HAA
5. Count people by recreation activity	1.0	BW,IR, Color,CIR	13	10	Color	HAA
6. Forest visitors by vehicle or pedestrian	.5	BW	10	8	Color	HAA,MAA
7. Count people in camps	1	BW,Color	4	2	Color	LAA
8. Count people with autos	1	BW,Color	4	2	Color	LAA
9. Count people with boats	1	BW,Color	4	2	Color	LAA
E. Wildlife						
1. Bald eagle nest trees	1.0	CIR	11	9	CIR	HAA,MAA
2. Wild horse-burro use area	3.0	CIR	21	15	CIR	HAA

Aldrich, Robert C. 1979. Remote sensing of wildland resources: A state-of-the-art review. USDA For. Serv. Gen. Tech. Rep. RM-71, 56 p. Rocky Mt. For. and Range Exp. Stn., Fort Collins, Colo.

A review, with literature citations, of current remote sensing technology, applications, and costs for wildland resource management, including collection, interpretation, and processing of data gathered through photographic and nonphotographic techniques for classification and mapping, interpretive information for specific applications, measurement of resource parameters, and observations and counts of occurrences.

Keywords: Remote sensing, photographic, nonphotographic, classification, mapping, interpretation, measurements, observations, wildland, forest, range, soils, water

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U.S. Department of Agriculture
Forest Service

Rocky Mountain Forest and Range Experiment Station

Rocky Mountains

Southwest

Great Plains

The Rocky Mountain Station is one of eight regional experiment stations, plus the Forest Products Laboratory and the Washington Office Staff, that make up the Forest Service research organization.

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Research programs at the Rocky Mountain Station are coordinated with area universities and with other institutions. Many studies are conducted on a cooperative basis to accelerate solutions to problems involving range, water, wildlife and fish habitat, human and community development, timber, recreation, protection, and multiresource evaluation.

RESEARCH LOCATIONS

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Bottineau, North Dakota
Flagstaff, Arizona
Fort Collins, Colorado*
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Lincoln, Nebraska
Lubbock, Texas
Rapid City, South Dakota
Tempe, Arizona

*Station Headquarters: 240 W. Prospect St., Fort Collins, CO 80526